

A family of perfect configuration lenses of revolution (*)

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SUMMARY. — A family of configuration lenses is described which collimate the rays from a point feed on a cone of varying aperture. The RCA « lamp-shade » (fig. 5), the RINEHART-LUNEBERG lens (fig. 7) and the sphere are members of this family. A fourth member is worth noticing (fig. 12) for its excellent scanning properties.

SOMMAIRE. — Une famille de lentilles de « configuration » est décrite; ces lentilles permettent d'obtenir un faisceau de rayons parallèles à partir d'un point source (d'ondes courtes) placé sur un cône d'ouverture variable.

L'abat-jour de la R. C. A., (fig. 5), la lentille de RINEHART-LUNEBERG (fig. 7) et la sphère en sont des cas particuliers. Un quatrième exemple (fig. 12) mérite d'être signalé pour ses excellentes possibilités d'exploration angulaire.

ZUSAMMENFASSUNG. — Eine Gruppe von Konfigurationslinsen wird beschrieben, bei denen die von einem Punkt ausgehenden Strahlen in einen Kegel veränderlicher Apertur gebündelt werden. Der R. C. A. « Lampenschirm », (Abb. 5) die Linse nach RINEHART-LUNEBERG (Abb. 7) und die Kugel gehören in diese Gruppe.

Auch die Linse nach Abb. 12 gehört dazu und ist wegen ihrer guten Eigenschaften besonders zu erwähnen.

Introduction. — Differential geometry and the theory of RIEMANN spaces have been repeatedly applied to the treatment of geometrical optics in a continuous and non-homogeneous medium. However such investigations presented for a long time a merely academic interest. This was mainly due to the difficulty, or even impossibility, of realising a medium of variable refractive index with the very high degree of accuracy which is required in optics.

In recent years the situation has considerably changed due to the advent of microwave techniques and of their applications. In the first place it is today quite possible to produce an artificial dielectric where the refractive index is a function of position, sufficiently smooth to be considered continuous for microwave applications. In the second place microwaves can be constrained to travel along a surface, as will be explained below. This is a propagation in a two-dimensional RIEMANN space.

On the other hand these kinds of media have proved very useful in the design of a number of ingenious devices for wide-angle and high-speed scanning. As a consequence the application of RIEMANN geometry to geometrical optics has again attracted the attention of many workers. The subject seems still to be far from exhausted and offers a lot of interesting possibilities both to the inventor and to the mathematician.

In the present paper we shall first give a brief outline of previous work which is necessary to understand what follows. Then we shall present a family of two-dimensional non-Euclidean spaces which are perfect optical instruments and correspond each to a possible high-speed scanning system. Three of the

systems which are already well known will be found to be only particular cases of the general class.

Previous Work. — Early workers in the field of geometrical optics of non-homogeneous media were mainly concerned with media existing in nature such as the terrestrial and solar atmospheres. Only occasional attempts were made to realise artificial non-homogeneous media of cylindrical symmetry with a view to investigating the properties of the eyes of the insects [1].

A theoretical contribution of great interest was made by J. C. MAXWELL in 1854 [2]. He described a system with spherical symmetry having the properties of a perfect optical instrument. MAXWELL stated that his investigation had been suggested by the contemplation of the crystalline lens of a fish; for this reason his system has since been known as « Maxwell's fish-eye ». We shall write the refractive index of the MAXWELL fish-eye in the form

$$(1) \quad n = \frac{2}{1 + r^2}$$

where r represents the distance from the centre. It can be shown that with this system a general point A of space (fig. 1) is perfectly imaged at a point A' ali-

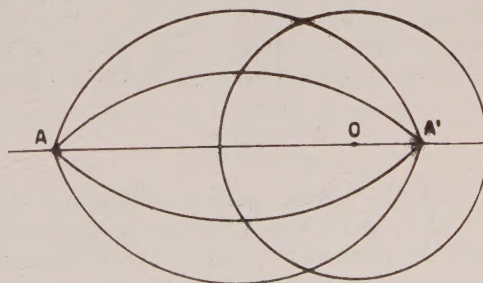


FIG. 1. — MAXWELL fish-eye: a point source A is perfectly imaged at A'.

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igned with A and with the centre of symmetry O. Taking O as origin, the abscissae x, x' of A, A' are found to obey the relation $xx' = -1$. On the unit sphere ($r = 1$) the refractive index is unity. A point A of this sphere (fig. 2) will be imaged at the diametrically opposite point A'.

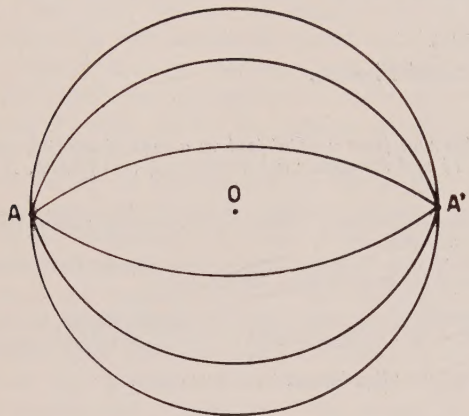


FIG. 2. — MAXWELL fish-eye: a point source A on the unit sphere is imaged at the diametrically opposite point A'.

Another remarkable system with spherical symmetry was described in comparative recent times by R. K. LUNEBERG [3]. The refractive index is represented by

$$(2) \quad n = \sqrt{2 - r^2}$$

for $r \leq 1$ and by $n = 1$ for $r > 1$. Every point A at infinity (fig. 3) has its perfect image A' on the unit sphere.

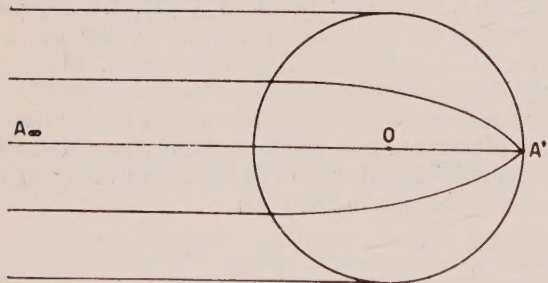


FIG. 3. — LUNEBERG lens: a point source A located at infinity is perfectly imaged on the unit sphere at A'.

A powerful tool for the treatment of the geometrical optics of non-homogeneous media is provided by the theory of RIEMANN spaces. The starting point for this application is represented by the Fermat principle

$$(3) \quad \delta \int n \, ds = 0$$

stating that the optical path is stationary along a ray. Consider then a non-Euclidean space corresponding point by point to the physical (Euclidean) space and having its line element ds_F given by

$$(4) \quad ds_F = n \, ds$$

This space will be called the FERMAT space corresponding to the given distribution of refractive index. By substituting from (4), Eq. (3) transforms into

$$(5) \quad \delta \int ds_F = 0$$

that is into the condition for a geodesic. Hence we can conclude that the light rays of the physical system characterized by a given distribution of refractive index n correspond to the geodesics of the FERMAT space characterized by (4). This correspondence can be very useful since the properties of the geodesics of RIEMANN spaces have been extensively investigated in differential geometry and can be converted into as many properties of the light rays in non-homogeneous media.

The correspondence between the physical and the FERMAT space is a conformal mapping so that the angles are preserved.

A further property of the FERMAT space which shows its profound physical significance has been demonstrated by E. BORTOLOTTI [4] and later, but independently, by R. K. LUNEBERG [5]. Both the electric and the magnetic vectors of a light wave travelling along a geodesic of the FERMAT space remain parallel to themselves in the sense of LEVI-CIVITA. This property may be utilised for determining the direction of polarization of a ray having passed through the system under investigation.

The FERMAT space corresponding to the MAXWELL fish-eye is readily found to be a non-Euclidean space of constant positive curvature, or the three-dimensional equivalent of a sphere. The geodesics of a sphere are great circles and all great circles through a point intersect each other at the diametrically opposite point. This simple remark gives us a very clear and deep insight into the properties of MAXWELL's fish eye.

The author has also investigated the medium corresponding to a FERMAT space of constant negative curvature [6]. A medium of this type is met in submarine acoustics. The methods of differential geometry prove very powerful in this case.

A. SIGNORINI [7] has demonstrated the following property holding for any medium whose FERMAT space has a constant curvature: All light rays are circles and all wave surfaces generated by point sources are spheres (with moving centres).

The interest in the geometrical optics of non-Euclidean spaces has considerably revived with the advent of microwaves. As is well known a wave guide can be formed by two plane-parallel metal plates. The propagation is not substantially disturbed if the plates are bent to assume any desired shape (fig. 4) provided that parallelism is maintained and that the radii of curvature are everywhere large with respect to the wavelength. If the spacing between the plates is sufficiently small we may imagine the wave propagation to occur along the mean surface. Thus we shall deal with a two-dimensional medium having in general a



FIG. 4. — Parallel-plate wave guide.

non-Euclidean metric. The rays will be geodesics of the surface.

Among these surface wave guides, for which the name of *configuration lenses* has been proposed [8] there are some which represent perfect (two-dimensional) optical systems. They have offered a number of new and brilliant solutions to the problem of wide-angle scanning [9], [10]. The problem is that of collimating the radiation from a point feed in such a way that the radiated beam turns through a substantial angle when the feed moves along a given curve (the *feed-line*, preferably a circle).

The simplest type of configuration lens has been developed by H. B. DE VORE and H. IAMS [11]. It consists of two developable surfaces, namely a cone of 60° aperture and a plane base (fig. 5). The rays

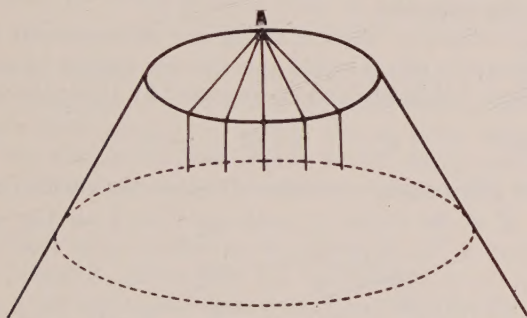


FIG. 5. — The « lamp-shade » configuration lens : a point source A is perfectly imaged at infinite distance on the cone.

from the feed A which moves along the circumference of the base (feed-line) turn out collimated on the conic surface. Because of its peculiar shape this configuration lens is sometimes referred to as the *lamp-shade* lens. In order to utilize the collimated beam for scanning purposes a part of the cone must be deformed and developed on a plane.

A second configuration lens has been described by R. F. RINEHART [12]. His investigation was based on a very interesting approach. Consider Eq (2) to represent a distribution of refractive index on a plane, that is a two-dimensional LUNEBERG lens. If a configuration lens can be found having the same metric as the FERMAT space corresponding to Eq (2) this configuration lens will have the same collimating properties as the Luneberg lens. More generally, consider a plane where the refractive index is any given function $n(r)$ of the radius alone. The corresponding FERMAT space will have its line element given by

$$(6) \quad ds_F^2 = n^2(dr^2 + r^2 d\theta^2) .$$

To simplify the investigation we shall require the configuration lens equivalent to the FERMAT space (6) to be a surface of revolution. The surface will be specified by its meridional curve. We shall choose as coordinates in the meridional plane the distance ρ from the axis (fig. 6) and the arc l of the meridional curve. The line element of the surface will be given by

$$(7) \quad ds^2 = dl^2 + \rho^2 d\theta^2 .$$

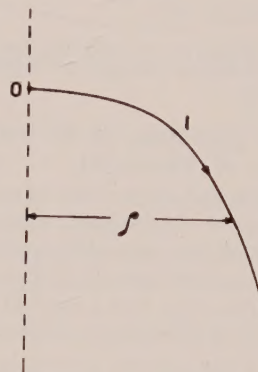


FIG. 6. — Meridional curve of a general configuration lens of revolution.

By requiring identity of (6) and (7) we find

$$(8) \quad n(r) r = \rho$$

and

$$(9) \quad n(r) dr = dl .$$

The last equation yields

$$(10) \quad l = \int_0^r n(r) dr .$$

Finally by solving (8) for r and substituting into (10) we shall obtain a relation between l and ρ which represents the equation of the meridional curve. In the case of the refractive index (2) RINEHART has obtained

$$(11) \quad l = \frac{1}{2} (\rho + \arcsin \rho) .$$

The corresponding meridional curve is shown in figure 7, while figure 8 is a qualitative representation of the complete RINEHART-LUNEBERG lens showing some rays from the point feed A. The surface must be provided with a plane flange on which the rays are collimated. The flange is attached along the feed-line.



FIG. 7. — Meridional curve of the RINEHART-LUNEBERG lens.

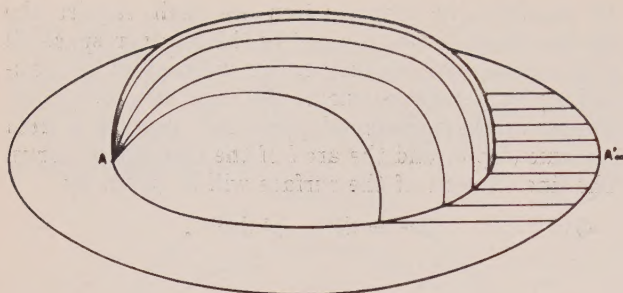


FIG. 8. — RINEHART-LUNEBERG lens: the point source A is perfectly imaged at infinite distance on the plane rim.

A Geometrical Condition to be Fulfilled by Configuration Lenses of Revolution. — We shall now give a rather general definition of a configuration lens of revolution for high-speed scanning. Both the lens of figure 5 and the lens of figure 8 will be found to be particular cases of this definition.

Every lens of this type has a central part (hereafter to be called the *core*) formed by a surface of revolution. The outer part of the lens is a cone of suitable aperture attached to the core along a parallel. The same parallel represents the feed-line. The rays through a point of the feed-line after traversing the core are collimated over the cone surface.

The lamp-shade lens and the RINEHART-LUNEBERG lens represent special cases where the apertures of the outer cones are 60° and 180° respectively.

We shall work out a geometrical condition which is necessary for perfect collimation over the cone surface. Let the circle VIC (fig. 9) represent the feed-

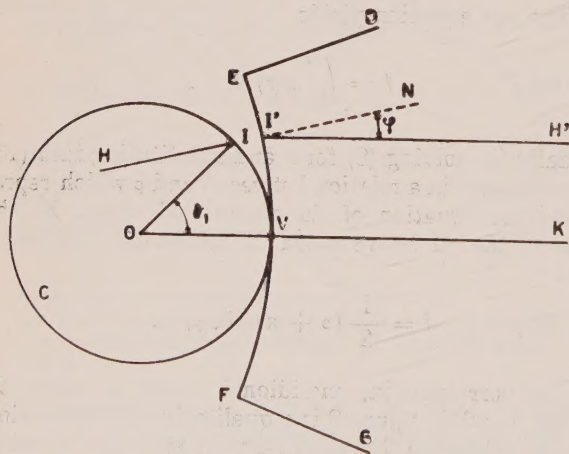


FIG. 9. — Geometrical relations between the core and the cone in a configuration lens of revolution.

line, i. e. the boundary of the core and DEFG a portion of the cone developed in the plane of the feed-line. If we take as unity the radius OV of the core and denote by R the radius of the circle EVF, it is evident that the angular aperture 2α of the cone will be given by

$$(12) \quad \sin \alpha = \frac{1}{R}$$

Consider a ray from the core intersecting the feed-line in the direction HI which makes an angle φ with the normal to the line ⁽¹⁾. This ray will enter the cone at a point I' which coincides with I in the actual lens. Hence we shall have $VI' = VI = \theta_1$. Besides the angle made by the ray I'H' with the normal I'N will be equal to φ (as could readily be shown by a straightforward application of the FERMAT principle). On the other hand in order to obtain collimation we shall require I'H' to be parallel to VK; consequently $\varphi = VI'/R = \theta_1/R$ and by (12)

$$(13) \quad \varphi = \theta_1 \sin \alpha$$

This is the required condition. The angles of incidence of the rays on the feed-line must be proportional to the azimuths of their points of incidence.

A Class of Non-homogeneous Media Corresponding to Perfect Configuration Lenses. — It seems difficult to work out directly the shape of a core obeying the condition of the preceding section. We shall begin instead by giving a class of plane distributions of refractive index which satisfies that condition. Then by considering the corresponding FERMAT spaces it will be easy to develop a class of configuration lenses of the type required.

The refractive index meeting our requirements is a function of r which in the general case cannot be written down explicitly and is expressed by the relation

$$(14) \quad n^2 r^2 = n^{1/p}(2 - n^{1/p})$$

where p is a positive number. It is readily verified that $n = 2^p$ at the centre ($r = 0$) and $n = 1$ on the unit circle ($r = 1$). It is also of interest to note that (14) for $p = 1$ reduces to (1) (MAXWELL fisheye), for $p = 1/2$ reduces to (2) (LUNEBERG lens) and for $p = 0$ gives $n = 1$ (homogeneous disk). The function $n(r)$ is plotted in figure 10 for different values of p .

Let us now determine the path of a ray which originates at a point A of the unit circle (fig. 11) and includes an angle φ with the radius vector at that point. As is well known, in a spherically symmetrical medium the product $nr \sin i$ where i represents the angle made by the ray with the radius vector is a constant along the ray (BOUGUER theorem). Hence, by considering that both n and r are equal to unity on the unit circle, we see that when the ray intersects the unit circle a second time at I its angle of incidence will again be φ .

Ray propagation in a spherically stratified medium has been thoroughly investigated [13], so we may apply directly some well-known results. Referring to polar coordinates r, θ the differential equation of a ray has the form

$$(15) \quad d\theta = \frac{k dr}{r \sqrt{n^2 r^2 - k^2}}$$

⁽¹⁾ Note that neither HI nor the normal need be in the plane of the drawing. They are both in the tangent plane of the core at I.

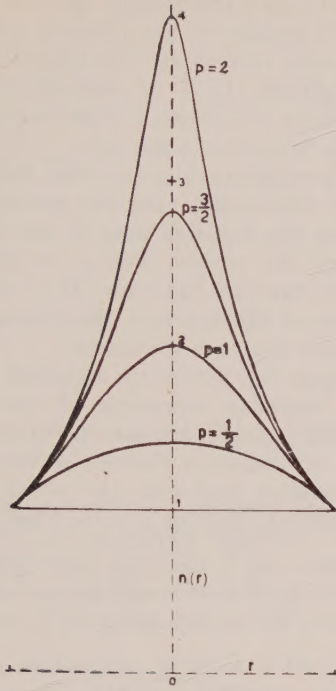


FIG. 10. — The refractive index as a function of r for different values of p .

where k represents the constant product $nr \sin i$.

To integrate this equation we shall refer to LUNEBERG's discussion [14] taking OV as polar axis. In our case simple analysis of (14), which will be omitted here, shows that nr is an increasing monotonic func-

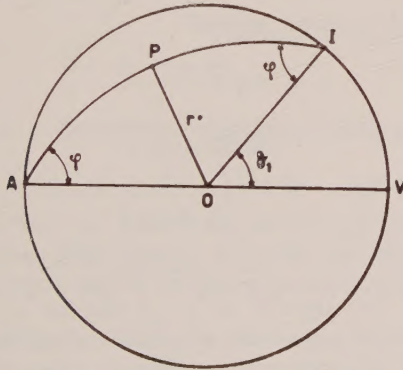


FIG. 11. — Trajectory of a ray within the unit circle.

tion of r . Consequently there will be a value r^* of r satisfying the equation $nr = k = \sin \varphi$ and representing the minimum distance of the ray from the centre (fig. 11). Until this minimum distance is reached at P the equation of the ray is given by

$$(16) \quad \theta = \pi + \sin \varphi \int_1^r \frac{dr}{r \sqrt{n^2 r^2 - \sin^2 \varphi}}.$$

Hence the azimuth θ^* of P will be represented by

$$(17) \quad \theta^* = \pi + \sin \varphi \int_1^{r^*} \frac{dr}{r \sqrt{n^2 r^2 - \sin^2 \varphi}}.$$

Beyond P the equation of the ray is given instead by

$$(18) \quad \theta = \theta^* - \sin \varphi \int_{r^*}^r \frac{dr}{r \sqrt{n^2 r^2 - \sin^2 \varphi}}.$$

whence the azimuth θ_1 of I is found to be

$$(19) \quad \theta_1 = \theta^* - \sin \varphi \int_{r^*}^1 \frac{dr}{r \sqrt{n^2 r^2 - \sin^2 \varphi}}.$$

Finally by combining (17) and (19) we get

$$(20) \quad \theta_1 = \pi - 2 \sin \varphi \int_{r^*}^1 \frac{dr}{r \sqrt{n^2 r^2 - \sin^2 \varphi}}.$$

Before evaluating the integral one has to replace n by its expression as a function of r derived from (14). Surprisingly enough the integration can be carried out by introducing a new variable x given by

$$(21) \quad x = n^2 r^2 = n^{1/p} (2 - n^{1/p}).$$

By solving for n we get

$$(22) \quad n = (1 + \sqrt{1 - x})^p$$

whence

$$(23) \quad r = x^{1/2} n^{-1} = x^{1/2} (1 + \sqrt{1 - x})^{-p}$$

and

$$(24) \quad \frac{dr}{r} = \frac{dx}{2x} + \frac{p dx}{2(1 + \sqrt{1 - x}) \sqrt{1 - x}}.$$

On the other hand we know that when r varies between r^* and 1 the product nr varies between $\sin \varphi$ and 1; hence, by (21), x will vary between $\sin^2 \varphi$ and 1. Taking into account this remark and substituting (21) and (24) into (20) we obtain

$$(25) \quad \theta_1 = \pi - \sin \varphi \int_{\sin^2 \varphi}^1 \frac{dx}{x \sqrt{x - \sin^2 \varphi}} - p \sin \varphi \int_{\sin^2 \varphi}^1 \frac{dx}{(1 + \sqrt{1 - x}) \sqrt{1 - x} \sqrt{x - \sin^2 \varphi}}.$$

Now one can verify the following indefinite integrals

$$(26) \quad \int \frac{dx}{x \sqrt{x - \sin^2 \varphi}} = \frac{2}{\sin \varphi} \arctan \frac{\sqrt{x - \sin^2 \varphi}}{\sin \varphi},$$

$$(27) \quad \int \frac{dx}{(1 + \sqrt{1 - x}) \sqrt{1 - x} \sqrt{x - \sin^2 \varphi}} = \frac{2}{\sin \varphi} \arcsin \left(\frac{\sin \varphi \tan \varphi}{1 + \sqrt{1 - x}} - \frac{1}{\cos \varphi} \right).$$

Upon substitution of (26) and (27) into (25) and after some transformations one finds the very simple result

$$(28) \quad \theta_1 = 2(1 - p) \varphi.$$

Thus we have shown that θ_1 is proportional to φ as was required by condition (13). This proves that

the relation (14) gives a refractive index having the property announced. The configuration lens corresponding to the FERMAT space of (14) will have the same property because a conformal mapping preserves the values of the angles.

The Perfect Configuration Lenses. — To find the equations of the configuration lenses corresponding to the refractive index (14) one has to apply (8) and (9). It is again expedient to consider the variable x introduced by (21). By combining (8) and (21) we have

$$(29) \quad x = \rho^2$$

and by substituting into (22) and (23)

$$(30) \quad n = (1 + \sqrt{1 - \rho^2})^p$$

$$(31) \quad r = \rho(1 + \sqrt{1 - \rho^2})^{-p}.$$

A differentiation of (21) gives

$$(32) \quad dr = (1 + \sqrt{1 - \rho^2})^{-p} \left[1 + \frac{p\rho^2}{\sqrt{1 - \rho^2}(1 + \sqrt{1 - \rho^2})} \right] d\rho.$$

This can be transformed into

$$(33) \quad dr = (1 + \sqrt{1 - \rho^2})^{-p} \left(1 - p + \frac{p}{\sqrt{1 - \rho^2}} \right) d\rho.$$

If the expressions (30) and (33) are introduced into (10) the integration can be carried out by inspection and we get

$$(34) \quad l = (1 - p)\rho + p \arcsin \rho.$$

This is the required equation (1). For each value of p we get a perfect configuration lens.

It is readily seen from (34) that p must be positive; for $p < 0$ would give $l < \rho$ and this is impossible for a real surface of revolution.

The angular aperture 2α of the cone to be attached to each lens can be derived from (13) and (28) and is found to be given by

$$(35) \quad \sin \alpha = \frac{1}{2(1 - p)}.$$

We shall now give a brief discussion of the results (34) and (35).

For $p = 0$ the core reduces to a plane disk ($l = \rho$) and the cone aperture is $2\alpha = 60^\circ$. We have the lampshade lens of figure 5.

When p is increased the core becomes a bulging surface and the cone aperture increases too. For $p = 1/2$ the core becomes the RINEHART-LUNEBERG lens (11)

(1) Note added in proof. The May 1954 issue of the *Jl appl. Phys.*, which was received in this country when the present paper was already submitted for publication, contains a contribution by K. S. KUNZ, who had independently discovered Eq (34). However KUNZ does not mention the cones with negative aperture and the lens of figure 12, which is the best member of the Family.

and the cone attains its maximum aperture $2\alpha = 180^\circ$.

If p is still increased in the interval $1/2 < p < 3/2$ the cone becomes imaginary ($|\sin \alpha| > 1$) and the lens cannot be realised. It is of interest to note that $p = 1$ would give $l = \arcsin \rho$, that is a sphere; this corresponds to MAXWELL's fish-eye.

For $p \geq 3/2$ we get again a real cone, but with negative aperture. This means that the radiation is collimated towards the tapering part of the cone instead of away from the vertex. For $p = 3/2$ we have $2\alpha = -180^\circ$, that is a flat cone. If p increases, the absolute value of the aperture diminishes, until for $p = \infty$ the cone becomes a cylinder.

From (34) one can derive by standard methods of calculus the cartesian equations of the meridional curves. To this end it is convenient to introduce for each curve a coordinate z directed downwards along the axis of rotation and with the origin at the top point of the curve ($z = 0$ for $\rho = 0$). Then by putting

$$(36) \quad w = \sqrt{\frac{p + (2 - p)\sqrt{1 - \rho^2}}{1 + \sqrt{1 - \rho^2}}}$$

and carrying out a lengthy integration one arrives at the cartesian equation required. Three cases must be distinguished. For $p < 2$ the cartesian equation is

$$(37) \quad z = 2(p - 1)\sqrt{p} \left(\frac{w}{2 - p - w^2} - \frac{1}{2\sqrt{2 - p}} \log \left| \frac{\sqrt{2 - p} + w}{\sqrt{2 - p} - w} \right| - \frac{1}{1 - p} + \frac{1}{2\sqrt{2 - p}} \log \left| \frac{\sqrt{2 - p} + 1}{\sqrt{2 - p} - 1} \right| \right).$$

For $p = 2$ we have instead

$$(38) \quad z = 4\sqrt{2} \frac{w - 1}{w}.$$

Finally for $p > 2$ we have

$$(39) \quad z = 2(p - 1)\sqrt{p} \left(\frac{1}{\sqrt{p - 2}} \arctan \frac{w}{\sqrt{p - 2}} - \frac{w}{w^2 + p - 2} - \frac{1}{\sqrt{p - 2}} \arctan \frac{1}{\sqrt{p - 2}} + \frac{1}{p - 1} \right).$$

To obtain the equations in explicit form one has to replace w by its expression (36). Equation (37) is not valid for $p = 1$; however we already know that $p = 1$ would give us a sphere.

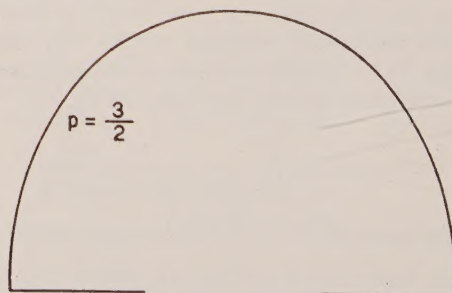
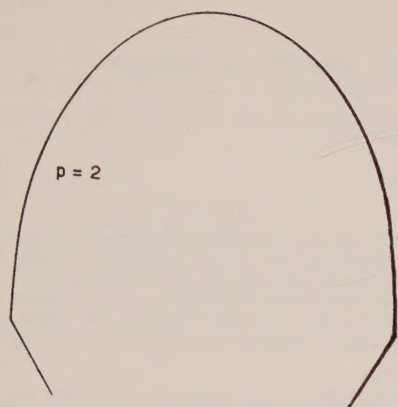


Fig. 12. — Configuration lens corresponding to $p = 3/2$.

FIG. 13. — Configuration lens corresponding to $p = 2$.

The meridional curves corresponding to $p = 1/2$, $p = 3/2$, $p = 2$ are shown by figures 7, 12, 13 respectively including some portions of the cones.

A very interesting case is that of $p = 3/2$. This lens presents some of the properties of the RINEHART-LUNE-

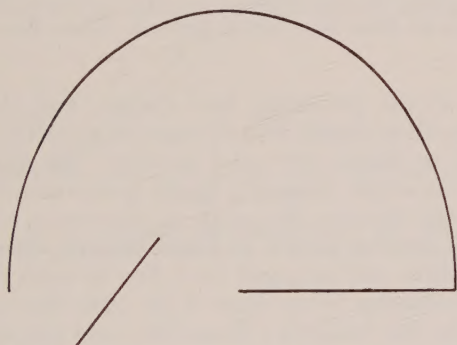


FIG. 14. — Combination of the lens of figure 12 with a plane mirror.

BERG lens with the additional advantage that by cutting the base disk along a diameter one can obtain a real line source which meets all requirements for good scanning as defined by S. B. MYERS [9]. Screening of the collimated beam by the opposite side of the core could very easily be prevented by means of a plane mirror (fig. 14) or by bending a portion of the base into a cylinder (fig. 15).



FIG. 15. — The lens of figure 12 with a portion of the basis bent into a cylinder.

Conclusion. — The lamp-shade lens, the RINEHART-LUNE-berg lens and the sphere (MAXWELL fish-eye) are members of a family of perfect configuration lenses which are completely described in the present paper.

Oddly enough the best scanning properties are presented by a fourth member of the family which had previously been overlooked. The meridional curve of this lens is shown in figure 12. In practice a plane mirror will be necessary for preventing the beam from being partially screened by the lens itself (fig. 14).

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Transparent fibres for the transmission of optical images

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SUMMARY. — An account is given of earlier experiments [2] in which a flexible bundle of fine glass fibres was successfully used for the transmission of optical images. Some more recent photometric and other studies of the optical properties of fibre bundles are described. The mechanism of transmission of light through these light channels is studied and experimentally verified. An account is given of a new machine for making bundles 75 cm long of fibres of smaller diameter, of the order of 25μ , and subsequently straightening the bundle so that all the fibres are of equal length. A study is made of different factors affecting the resolving power of such « static scanning devices » and measurements made on the resolution of periodic gratings are described. Some further applications of such fibres and fibre bundles are described.

SOMMAIRE. — Il a été montré dans une première publication [2] qu'un faisceau flexible de fines fibres de verre avait été utilisé avec succès pour la transmission d'images optiques.

On présente quelques études (photométriques et autres) concernant les propriétés optiques du faisceau de fibres.

Le mécanisme de transmission de la lumière à travers ces conduits lumineux est étudié et vérifié expérimentalement. On décrit une machine nouvelle permettant de fabriquer des faisceaux, longs de 75 cm et faits de fibres de petit diamètre de l'ordre de 25μ , et de redresser ensuite le faisceau pour que toutes les fibres soient d'égal longueur.

On étudie les différents facteurs agissant sur le pouvoir séparateur de tels « organes d'exploration statique » et l'on présente des mesures de résolution effectuées à l'aide de réseaux périodiques. Description de quelques autres applications de ces fibres optiques et faisceaux de fibres.

ZUSAMMENFASSUNG. — Es wird über frühere Versuche berichtet, bei denen ein biegsames Bündel von Glasfäden mit Erfolg für die Übertragung optischer Bilder benutzt wurde. Es werden einige neuere Untersuchungen — auch photometrischer Art — über die Eigenschaften solcher Faserbündel mitgeteilt. Die Versuche über den Vorgang der Lichtübertragung durch solche Lichtkanäle stehen mit den Überlegungen im Einklang. Mit Hilfe einer neuen Maschine kann man Faserbündel von 75 cm Länge herstellen, bei denen der Querschnitt der einzelnen Faser in der Größenordnung von 25μ liegt. Die verschiedenen Einflüsse auf das Auflösungsvermögen und das Raster werden untersucht und das Auflösungsvermögen an Hand von Gittern gemessen. Solche Fasern und Faserbündel lassen sich für verschiedene Zwecke verwenden.

1. Introduction. — A new kind of optical unit using the principal of « static scanning » was recently described [2] in which use was made of a bundle of fibres of transparent material to convey optical images along flexible axes. Some preliminary experiments and some properties of such systems were described. A brief description of the mechanism used for aligning the fibre bundles in the initial stage was also given. The results obtained using 60μ diameter fibres giving 4 lines/mm resolving power and good light transmission, lead to the necessity for more precise evaluation of the system. It was found desirable to go into more detail regarding the mechanism of light transmission through such light channels and photometric data was obtained. It was then proposed to construct a fibre bundle of 75 cm length using 25μ (or less) diameter fibres. The principle of a new machine which was designed for this purpose is described in what follows. This machine makes possible the construction of a 75 cm long fibre bundle, all the fibres being subsequently made of equal length by means of a cam device, which is also described. The speed of winding is increased by using « multistart guide pulleys ». Different factors affecting the resolving power of such systems are discussed. Some more recent applications of fibres for « field flattening » of optical lens systems and « light funnels » for conduction of light from, for example, a circular star image to a slit shape, are also dealt with.

For « field flattening », the entrance end of the fibre bundle is smoothly curved to the shape of the image

surface of the preceding lens system and the exit end of the fibre bundle is made plane or given the curve required to flatten the field through the eyepiece. For use as « light funnels » in the spectroscopic analysis of star images, the image of the star is made to fall on a circular bundle of fibres and the other ends of the fibres are arranged in a line to form the slit of the collimator. Thus most of the light flux contained in the star image is « funnelled » into the spectrometer slit.

2. Conduction of light along a single fibre. — Theoretical considerations suggest that visible light can be conducted through fibres down to about 12μ in diameter, whereas below these diameters diffraction effects become predominant, the fibres act as wave guides and a significant fraction of the energy escapes through the walls.

To test the conduction of light through long fibres a B. S. C. glass fibre 25μ in diameter and 75 cm long was used. Light from a strong source was condensed on one end of the fibre which was made to lie along a sharp curve, the other end being observed under a low power microscope — sufficient light was conducted through the fibre to give a bright image in the microscope.

It can be easily seen that the length of path along a multiply reflected ray is $L \sec I'$ where L is the axial length of the fibre and I' the angle the ray in the glass makes with the axis of the fibre. It is independent of the diameter of the fibre D . In a straight fibre the direction of the emergent ray is the same as or opposite to that of the entrance ray according as the num-

(*) Paper presented to Florence Meeting on Problems in Contemporary Optics (10-16 september, 1954).

ber of reflections is even, or odd. It can also be seen that the number of reflections in a straight fibre is $L \tan I'/D$. In a fibre of 25μ diameter for $I = 10^\circ$ and $N = 1.5$ the number of reflections is 116 per 2.54 cm of length. The enormous number of reflec-

tions in the fibre indicate the necessity of keeping the fibre surface very clean otherwise light is lost at every reflection.

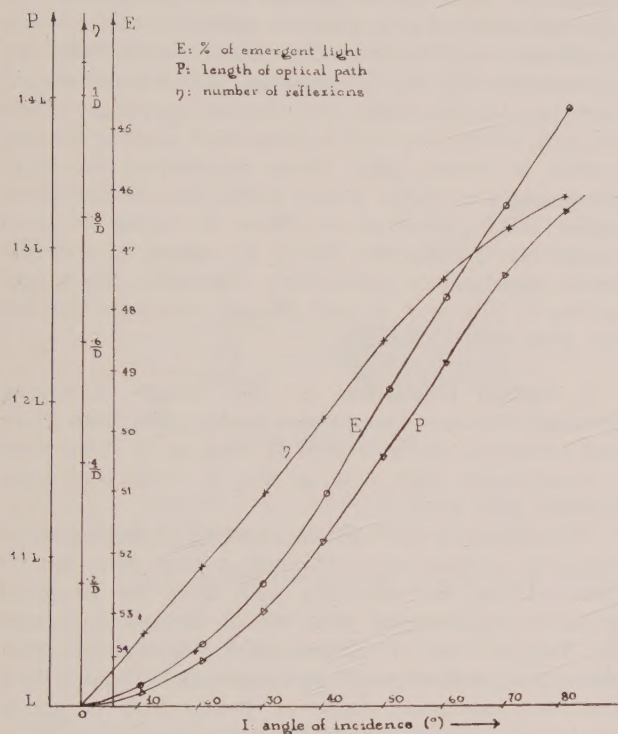


FIG. 1. — Transmission, path length and number of reflections as a function of angle of incidence.

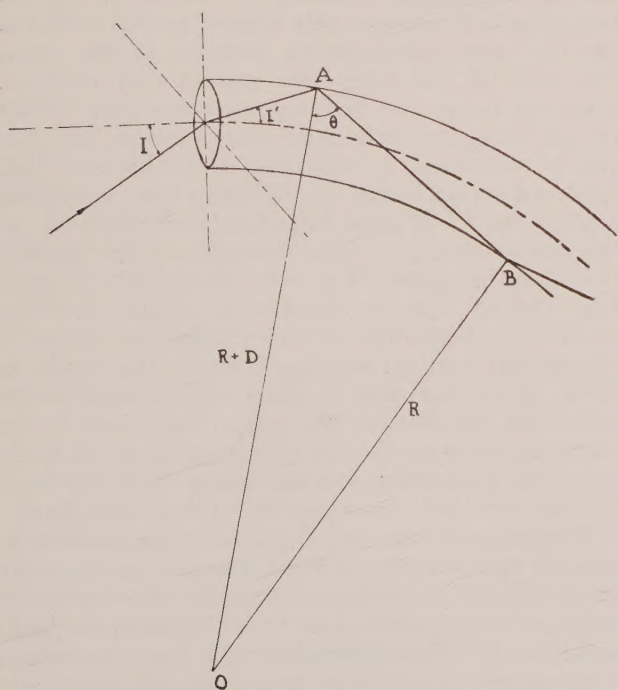


FIG. 2. — Ray path in a curved fibre.



FIG. 3. — Polar diagram of light emerging from a fibre.

The absorption of light during its passage through the fibre depends on the length of path and the absorption coefficient of glass. The transmission of the fibre T for a refracted beam at an angle I' is given by $\log_e T = -\alpha L \sec I'$. For a fibre of 75 cm axial length and co-efficient of absorption 2 % per inch, the percentage emergent light is 51 % for a ray inclined at 40° to the axis and approx. 54 % for the axial ray. The accompanying graph figure 1 gives the length of path, number of reflections and percentage transmission of straight fibres for light at different incident angles.

It can be seen by reference to figure 2 that for fibres of material with refractive index 1.5 to be used for light incident at angles up to 40° to the axis the allowable bending radius is approximately 3 times the diameter of the fibre before the incidence is less than critical. So long as the fibre is bent over a radius greater than three times its diameter there is no danger if light escaping from the wall.

If light is condensed on a small aperture placed on the axis at one end of a straight glass rod, whereby a cone of light is passed axially through the cylinder, then if we put a screen at the further end, we observe annular dark and bright rings. Each ring corresponds to a reflection that a part of the light cone suffers at the walls of the cylinder. Figure 3 illustrates this polar distribution of light at the exit end of the cylinder. It was found that, in spite of the ring formation, the extreme angle of the exit cone is equal to

that of the entrance cone. The number of bright rings is equal to the number of reflections that the extreme ray suffers.

Fibres drawn from molten glass or other materials are found to suffer from slight inhomogeneities. A collimated beam passed through a straight glass rod of approximately 1 mm diameter placed between cross polaroids, was found to show the characteristic fan appearance (fig. 4). It suggests that the strata of varying refractive index have circular symmetry about the axis, which may well indicate that there is a stress system in drawn glass fibres accounting for their great tensile strength. FAUST (1952) has studied these radial inhomogeneities in fibres in terms of local variations of refractive index, by means of multiple beam interference microscopy. Optically inhomogeneities of this kind do not present any difficulty for the present applications.

3. Optical Insulation. — The image conveying property of a bundle of fibres could suffer from glare and thereby a deterioration in contrast if there were a considerable light leakage due to frustrated total internal reflection.

The penetration of light incident at an angle greater than the critical angle through a thin film can be demonstrated by reflecting light from the diagonal face of a right angled prism which is separated from the diagonal face of another right angled prism by a thin film of dielectric of lower index. It has been shown that the maximum depth of penetration is about 3λ for glass-air interfaces. Experiments were conducted to observe the conditions and magnitude of light leakage from a light conveying fibre into the neighbouring six fibres surrounding it. A bunch of fine and long glass rods were roughly aligned so that each rod has the same corresponding position at two ends. The ends of the rods were ground and polished. First, the image of a bright point source was formed on the triangular interstitial space between the rods and it was found by observing the other end that light had spread in the neighbouring rods, producing a glare due to air-glass refraction and reflections at the surrounding rods. This necessitated the blocking of interstitial spaces. It is to be noted that this blocking can be done by neither an opaque medium, which will absorb light at every reflection, nor by a transparent medium which will render the bundle of fibres optically a mass of nearly constant refractive index and thus destroy the optical insulation. It was found in practice that a very thin layer of finely powdered glass filling the interstices effectively blocked them without upsetting the optical insulation.

The image of a bright point source was focussed on the end face of a glass rod and it was found that with glass rods of 1 mm diameter, optical line contact is not easily established, and for this reason, no light leakage into the neighbouring rods was observed at the exit end.

An approximate calculation of the percentage of

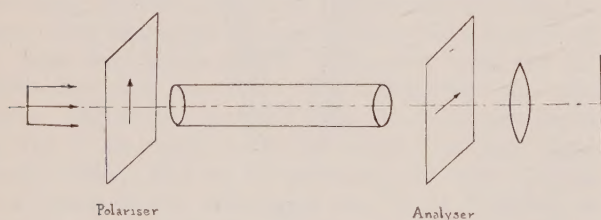


FIG. 4. — Strain polarisation in a drawn fibre.

light leakage from a light-conveying fibre into its neighbouring fibre assuming that there is optical line contact between the two fibres was made. The use of a fibre bundle 6.25 mm in diameter with 25 μ diameter fibres was considered and it is assumed that the preceding lens system works at ± 1 magnification. The inclination of the extreme ray from the marginal object point to the axis of the axial fibre is approximately 14° . This ray gets refracted in the fibre

the angle that the wave makes in the 2nd medium, $\cos \Phi_1 = i \sqrt{\left(\sin \Phi_0 \frac{N_0}{N}\right)^2 - 1}$ and thus the integrated percentage transmission was calculated for an incident wave with the plane of polarisation parallel or perpendicular to the plane of incidence.

It is thus seen that for fibres up to 25 μ diameter used in such a device with a preceding lens system used as described the maximum light flux leakage is of the order of 4 %, even if it is assumed that there is perfect line contact between a light conveying fibre and its neighbour. For this reason no coating of fibres was deemed to be necessary.

4. Resolving Power. — The resolving power of fibre systems depends primarily on the diameter and separation between the fibres. In practice there are some difficulties in obtaining perfect alignment, and fibres of constant diameter. However, continuous lengths of 25 μ diameter glass fibres have been obtained with ± 10 % variation in diameter, produced by a drawing process.

Two possible arrangements of fibres are shown in figure 7. In (a) the centres of fibres form square, and

($N = 1.5$ approx.) at approximately 10° . Since Φ_0 the angle that this ray makes with the fibre wall is $\frac{\pi}{2} - I' = 80^\circ$, in our calculation of light flux leakage Φ_0 goes from 80° to 90° . The arrangement is shown diagrammatically in figure 5.

The accompanying graph figure 6 shows the percent-

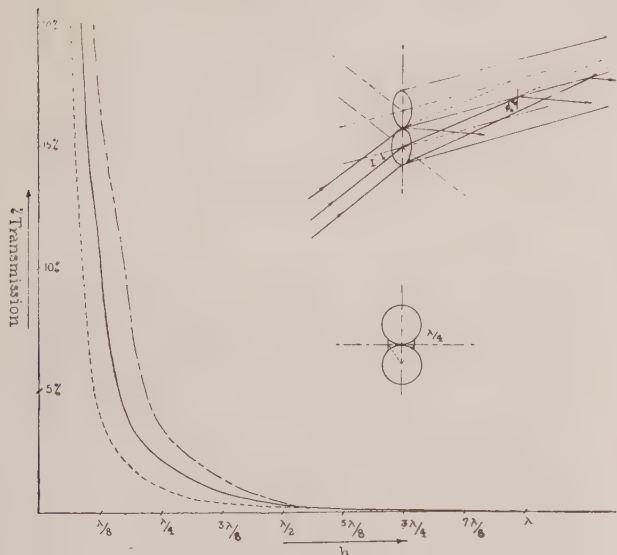


FIG. 6. — Leakage due to frustrated total internal reflections at adjacent fibres.

tage transmission of light for a wave incident at the fibre wall at an angle of 80° as a function of the separation between the fibres. The light leakage at this angle is significant only up to a distance of $\lambda/4$ where the transmitted light is approximately 1 %. In making these calculations the appropriate boundary conditions were applied by inserting the imaginary value of Φ_1

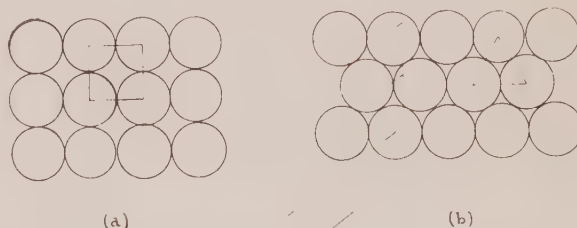


FIG. 7. — Geometrical arrangement of fibres.

in (b) the centres of fibres form equilateral triangles. It is found desirable both from the point of view of mechanical stability of the bundle of fibres and minimum loss of detail in the image, to choose arrangement (b) in which the centres of fibres form triangles and the dead area in the interstitial space is only 9 % as compared to 21.5 % in the case (a).

To test the alignment of the fibres, the image of a sharp edge is formed on one end of the fibre bundle and the other end of the bundle is observed under magnification. Light falling on any one fibre is distributed uniformly over the end face of the fibre on emergence. Moreover, if the image of a straight edge is formed on the object face of the fibre bundle, the boundary of the edge will not generally lie across a single row of fibres the centres of which are in a straight line, except in three particular positions. In consequence the image of the straight edge will be "broken", but the discontinuity will never extend more than one fibre diameter into the dark portion of the image. The image of the knife edge is scanned over the fibre bundle and rotated to change the orientation and the discontinuities in the edge image are observed in

all positions which gives us an evaluation of alignment.

Due to the relative positions of the fibres the detectable size of detail through the fibre bundles is of the order of twice the diameter of the fibres D , providing the alignment is perfect and the optical insulation between the fibres is maintained. Thus the resolving power in terms of lines per inch is approximately $1/4 D$ where the width of each dark and bright line is $2D$.

Measurements of resolving power were made on different lengths of fibre bundles varying from 3 cm to 10 cm, using $60\ \mu$ diameter glass fibres, by means of a grating test object. The intensity distribution in the image was measured by photographing the images of periodic gratings through the fibre bundle and subsequently measuring the density on a microdensitometer. The accompanying graphs (fig. 8) show the photo-

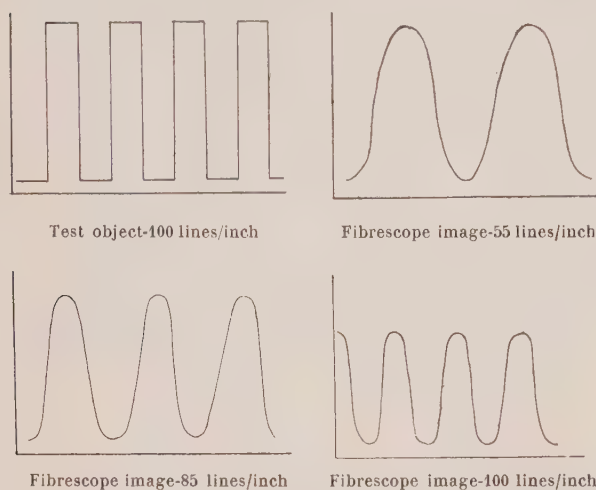


FIG. 8. — Photometric measurements on grating images.

metric measurements made on the image of periodic gratings from 55 to 100 lines/inch. Slight discontinuities on the curves were observed, due to the graininess of the fibres and fine scratches magnified on the microdensitometer. It is to be noted that $60\ \mu$ diameter fibres should theoretically give 4 lines/mm resolving power, which was easily obtained. It was observed that for periodic gratings above the limit of resolving power of the system, the image end gave a uniformly illuminated field.

It was observed during the measurements of resolving power that, when the test object was just above the limit of resolution and revolved in its own plane, the lines were not resolved in any positions but three. These three positions are those when the lines of the grating coincide with the line joining the centres of fibres, as is illustrated in figure 7.

5. Fibre Aligning Machine. — The method used for alignment of the fibres depends on the availability of nominally infinite lengths of fibres of constant diameter of some optically transparent and homo-

geneous material. Very fine fibres are being made of materials such as glass, quartz, nylons and polystyrene. Of these, glass fibres seem to be the only ones which satisfy most of the requirements and are easily procurable. Glass fibres are preferred also because of their great tensile strength.

Long lengths of glass fibres were uniformly wound on a former having a peripheral groove of square cross section, layer by layer, so that each layer was led to lie on the V groove made by the previous layer. This arrangement is preferred because of close packing and thereby minimum loss of detail and also because of the greater resulting mechanical stability. After winding the required number of layers, the bundle was gripped at different points by means of mechanical clamps which were an integral part of the former. The clamps were tightened, the fibre stack slipped from the former and sawn at different points between the clamps to yield different lengths of fibre bundles.

Fibre bundles of 0.6 cm cross section and of lengths varying from 2.5 cm to 12.5 cm, using $60\ \mu$ diameter fibres were produced in this way. These fibre bundles were tested for alignment and resolving power and gave the theoretically expected performance. The bundles were found to be very robust and flexible. The above mechanism had two inherent drawbacks, from the point of view of obtaining long lengths of finer fibre bundles. Firstly, the safe speed of fibre winding with this mechanism using $60\ \mu$ diameter fibres was about 750 cm/min. and 500 cm/min. for $25\ \mu$ diameter fibres. At this speed of winding with the above mentioned mechanism the proposed fibre bundle 0.5 cm cross section and 75 cm long using $25\ \mu$ diameter fibres would amount to winding approximately 50,000 metres of fibre at the winding speed of 500 cm/min. Secondly, when the fibre bundle is removed from the circular former and straightened, then, due to the topmost layer being wound on a greater radius than the bottom layer, there is a sag introduced in the bundle of fibres, all the fibres not being of equal length.

The new machine employed "multistart guide pulleys" to wind more than one fibre at the same time. The first layer is wound on the former by means of one of the leads. If n is the number of leads and N the number of turns required to wind one layer on the former then after every N/n turns the next fibre was fed in, and when any particular lead completed the layer, the fibre was fixed on the finishing end of the former through a slot and the lead brought back to restart the top most layer. A nut and screw mechanism with ten to one leverage was used to lead the slide on which the lead pulley is mounted. A countershaft is used to transmit power from the main spindle on which the former is mounted to the screw member S. This new mechanism (fig. 9) made it possible to transmit the precise lead to all the guide pulleys, using only one coarse lead screw. The portion of nut which is fitted on the end of the lever can be disengaged and by location on a locating screw brought back to the initial positions. The ten to one leverage employed

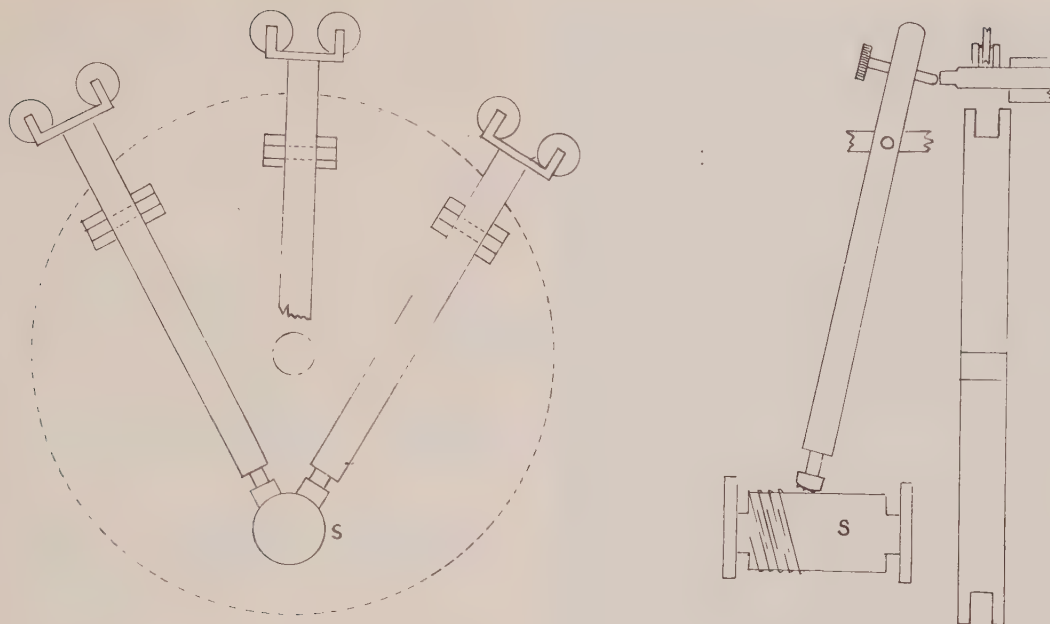


FIG. 9. — Multistart arrangement of guide pulleys.

minimises the errors of the lead screw and helps in transmitting motion whose pitch is equal to the diameter of the fibre used.

The difference in length of fibres in the bottom and top layer is $2\pi\delta R$ where δR is the thickness of the fibre bundle; it is independent of the diameter of the main former. In the cam device (fig. 10) used for the straightening of fibres, a part of the bundle of fibres from the main former is wound on a subsidiary roller of smaller radius, which takes up the variation of length in the fibres as they are unwound from the main former.

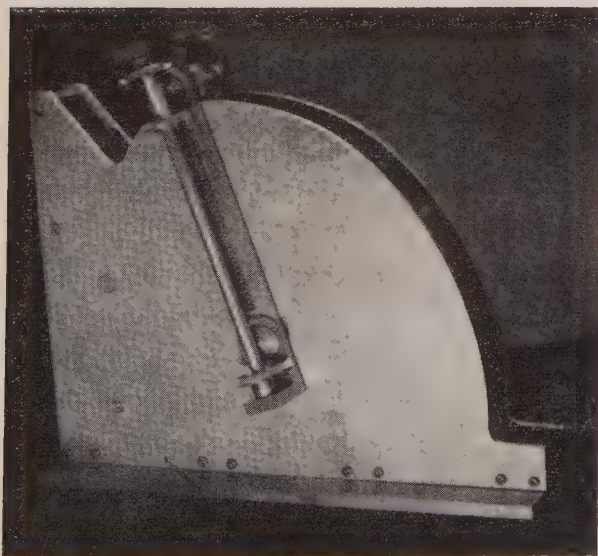


FIG. 10. — Photograph of cam mechanism.

Figure 11 shows the geometry of the system in which R is the radius of the former, and r is that of the subsidiary roller. The fibre bundle is sawn off at the top of the former along the y axis and fixed to the roller. The centre of the roller is then made to describe a locus defined by the cam, orientation of the roller

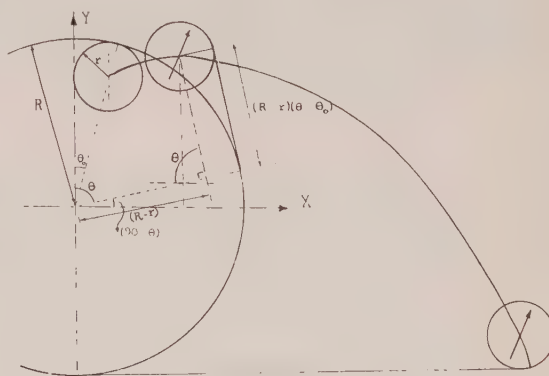


FIG. 11. — Geometry of cam straightening unit.

being kept constant in space. After traversing the required locus the centre of the roller r is in a position where part of the fibre bundle is wound round the semi-circle of the roller, and the remainder lies horizontally as a straight bundle of fibres, the co-ordinates of the centre of the roller, the parametric equations of the required locus, are

$$\begin{aligned} x &= (R - r) \sin \theta - (\theta - \theta_0) \cos \theta \\ y &= (R - r) \cos \theta + (\theta - \theta_0) \sin \theta \end{aligned}$$

in which θ, θ_0 are the angles indicated in figure 11.

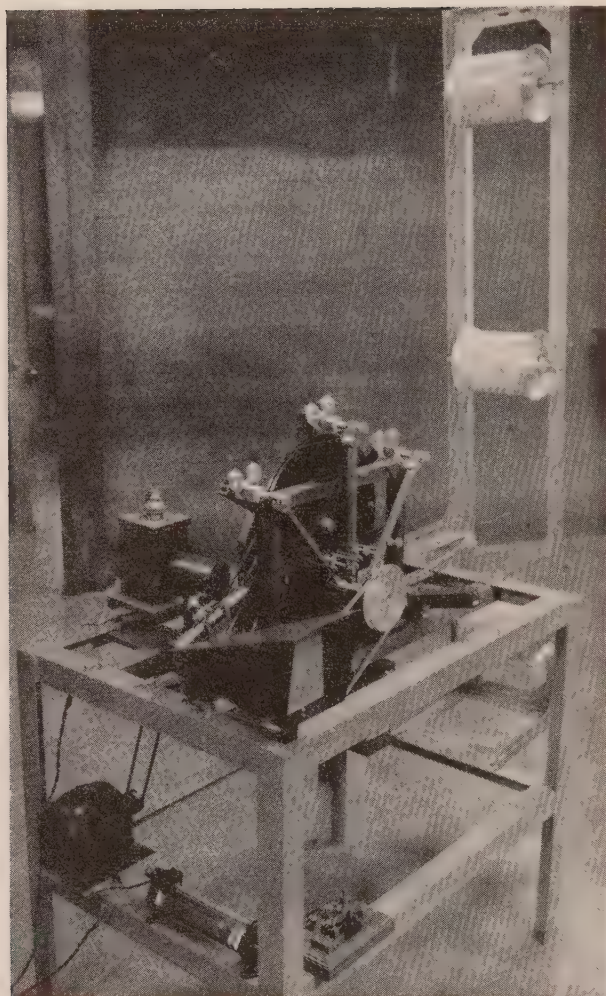


FIG. 12. — General view of aligning machine.

After the winding of fibres is completed, the former is transferred to the cam device. A simple system of bevel gears attached to a rotatable arm keeps the orientation of the roller constant in space, and the axle of the roller is spring loaded against the cam profiles. The cam is precisely formed so that the fibre length, as it is being unwound from the former is tangential both to the former and the roller, to avoid any dislodging of fibres. This whole operation is repeated on the other half of the former and the straight length in between the two rollers is taken for use.

Figure 12 shows a general view of the machine used for winding three fibres simultaneously. The fibre is unwound from three creel carriers which are mounted on ball races and a constant tension exerted by spring loading. Before going on the guide pulleys which provide the precise lead, the fibre passes over anti vibration pulleys which damp down any vibrations that may be set up in the running of the fibre. A micro-projector using a vertical illuminator is used to observe the winding of fibre as it proceeds.

6. Further applications. — An obvious use of fibre bundles is for transferring an optical image from a surface of given shape to one of a different shape. In particular a flexible viewing system of the kind illustrated in figure 13 may be designed in which the receiving surface has a curvature equal to the Petzval curvature of the objective system and the transmitted image is made to appear on a surface of such a shape that the image viewed by the simple eyelens is field-flattened.

An experiment of this kind was performed, and an image formed on a surface having a curvature equal to about 25 mm was successfully transferred to a plane.

Another useful application of systems of this kind is in what might be termed light funnels. If, for example, a light source of any other shape has to be used

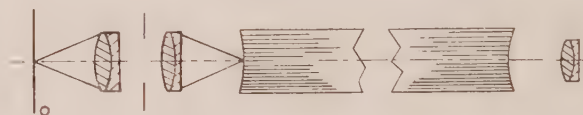


FIG. 13. — Use of fibre bundle with curved end faces.

in conjunction with an instrument having an annular entrance pupil, an annular bundle of fibres may be formed by clamping one end of a bundle in an annular clamp. The other ends of the fibres may then be gathered together into a shape similar to that of the source to be used. A condenser lens is then employed to form an image of the light source on the end face of the fibre bundle, the other end face thereby providing a secondary source of the desired shape.

Experiments of this kind have been undertaken with a view to funneling the light from a telescope star-image into a slit-shape suitable for illuminating the entrance of a spectrograph. In this way a considerable increase in efficiency seems possible to be achieved. Since the illumination is not constant over the area of the star-disc, care has to be taken to arrange a correct correspondence between each fibre position at the star-disc and the point on the entrance slit to which that fibre is led. In this way an approximately uniform illumination of the slit may be obtained.

7. Acknowledgement. — This work has been financed by a grant from the Royal Society Paul Instrument Fund. We are further indebted to Fibreglass Ltd. for their kindness in specially providing glass fibres.

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Eye-movements in relation to retinal action (*)

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SUMMARY. — Experiments are described in which the subject wears a contact lens to which small flat mirrors are attached. Beams of light reflected from these mirrors are received on a recording drum and may be used to record the rotations of the eye about three mutually perpendicular axes. When the subject is fixating a target as closely as possible, involuntary movements of the eyeball scan the visual axis through angles which are large compared with the visual angle corresponding to the diameter of a retinal receptor.

By using the beam reflected from the contact lens it is possible to present the subject with an object which moves so that its image on the retina remains stationary. It is found that the contrast sensitivity and visual acuity in respect of this image are much less than in normal vision. Results are discussed in connection with the recordings of nerve impulses made by HARTLINE [7]. It is suggested that appreciation of a pattern is controlled by a strong response of the receptors when the eye is scanned across the pattern by the normal involuntary movements.

SOMMAIRE. — Description d'expériences dans lesquelles le sujet porte un verre de contact auquel sont fixés 2 petits miroirs plans. Les rayons lumineux réfléchis par ces miroirs sont reçus sur un tambour enregistreur et peuvent être utilisés pour l'étude des rotations de l'axe par rapport à trois axes perpendiculaires. Si ce sujet fixe un point aussi attentivement que possible, des mouvements involontaires du globe oculaire font osciller l'axe visuel dans des angles qui sont grands comparativement au diamètre angulaire des récepteurs rétiniens.

En utilisant le rayon réfléchi par la lentille de contact, il est possible de présenter au sujet un objet se déplaçant de telle sorte que son image sur la rétine reste stationnaire. On trouve que la sensibilité au contraste et l'acuité visuelle pour cette image sont moindres qu'en vision normale. Discussion des résultats en fonction des mesures d'impulsions nerveuses dues à HARTLINE [7].

ZUSAMMENFASSUNG. — Die Versuchspersonen tragen ein Kontaktglas, an das kleine ebene Spiegel befestigt sind. Die von diesen Spiegeln reflektierten Lichtstrahlen werden aufgezeichnet und zur Messung der Augenbewegungen um drei zueinander senkrechten Achsen benutzt. Auch bei möglichst scharfem Fixieren eines Zieles erfolgen unwillkürliche Bewegungen des Augapfels um die Sehachse über Winkel, die im Vergleich zu dem Winkel, welcher dem Durchmesser des einzelnen Netzhautelementes entspricht, beträchtlich sind.

Mit Hilfe des von dem Kontaktglas reflektierten Lichtstrahls ist es möglich, der Versuchsperson ein Ziel darzubieten, welches sich so bewegt, dass sein Bild auf der Netzhaut stets auf die gleiche Stelle fällt. Es wird befunden, dass für dieses Bild die Kontrastempfindlichkeit und Sehschärfe viel niedriger als im normalen Sehen sind. Die Versuchsergebnisse werden im Bezug auf die von HARTLINE [7] angestellten Aufzeichnungen von Nervenimpulsen erörtert. Es wird angeführt, dass insofern es sich um die Betrachtung von gestalteten Gebilden handelt, die Betrachtung solcher Gebilde durch starke Reaktionen der Netzhautelemente geregelt wird, während das Auge durch normale unwillkürliche Bewegungen über das Gebilde hinweg getragen wird.

1. Introduction. — LORD and WRIGHT [8] give a summary of work on eye-movements up to 1950 and accounts of later work are given by BARLOW [2], DITCHBURN and GINSBORG [4] and RIGGS, ARMINGTON and RATLIFF [12]. Detailed reference to earlier work will not be made in the present paper but it may be stated that none of the results presented here are in conflict with the results obtained by other workers in recent years. The work quoted above shows that, even when the subject is looking as steadily as he can at a well-defined fixation point, the eye is never free from movement. There is a high frequency rotation of the eyeball which vibrates the retinal image of the object with an amplitude approximately equal to the intercone distance. The eye also moves so that the image of the fixation point drifts slowly in an irregular way, being brought back near to the centre of the fovea by flicks which occur about once a second. These two movements allow the image of the fixation point to wander over a retinal region of about 100 μ diameter containing about 1500 cones.

By a device which will be described below it is possible to produce an « object » whose image on the

retina does not move in response to eye-movements. Observations on this stabilised retinal image were made by the present writer in 1946 but were not published then owing to uncertainty concerning experimental conditions. The first publication was made by DITCHBURN and GINSBORG [3]. Shortly afterwards RATLIFF [10] reported that he had obtained the stabilised retinal image and gave the results of a detailed investigation on visual acuity.

2. Experimental methods. — The apparatus used by DITCHBURN and GINSBORG for recording eye-movements is shown in figure 1. Light from the high pressure mercury arc S is passed through a heat removing filter F and focussed on to the pin-hole at A. Light from this pin-hole is focussed by the lenses L_2 and L_3 upon the plane mirror M which is worked on the contact lens. A system of two slits, S_1 and S_2 , is placed as shown. The image of one of these slits is focussed directly by the lens system L_3 upon the drum camera C. Light from the other slit passes through a prism which rotates the image from horizontal to vertical before it is focussed upon the drum camera. We thus have the essentials of a projector system in which the maximum light is passed through the

(*) Paper presented to Florence Meeting on Problems in Contemporary Optics (10-16 september, 1954).

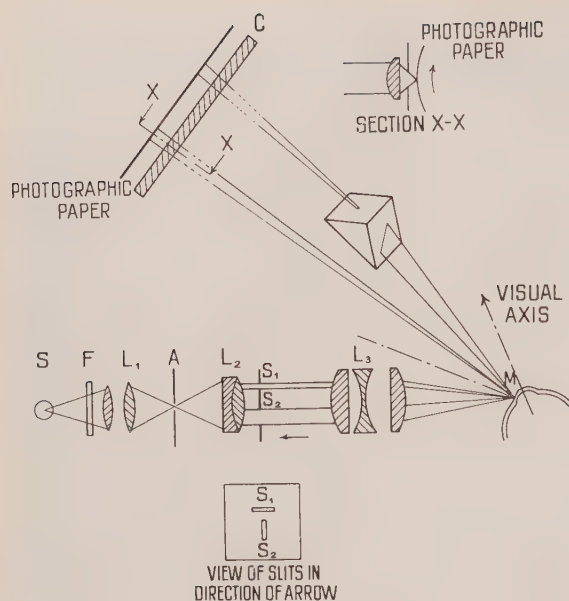


FIG. 1. — Apparatus for studying eye movements by DITCHBURN and GINSBORG.

stop formed by the small mirror *M* but the image of the target is formed at the correct place for recording. The plane mirror is worked on the corneal portion of the contact lens at approximately 35° to the visual axis. With this apparatus it is possible to record angular rotations (*H*) in a horizontal plane and (*V*) in a vertical plane including the visual axis. It is necessary to divide by the cosine of the angle between the normal to the mirror *M* and the visual axis in calculating the angular rotations (*V*) from the record of the reflected beam.

The modifications introduced by FENDER are shown in figure 2. The contact lens has been fitted with a

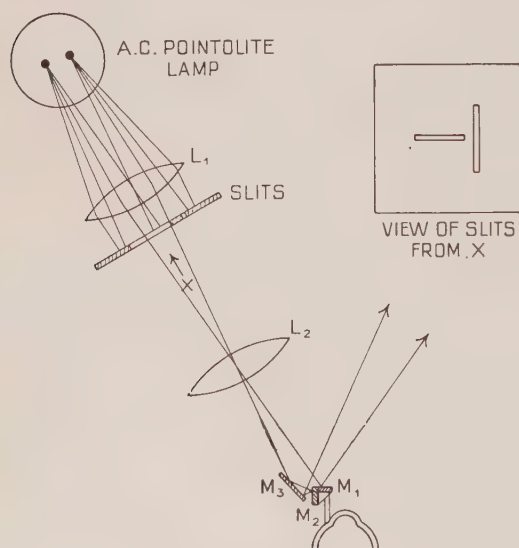


FIG. 2. — Modification to Eye-movement apparatus introduced by FENDER.
*L*₁ and *L*₂ are good quality photographic lenses.

small plastic rod, and two mirrors, mutually at right-angles, are mounted upon this stalk. The source of light is now an alternating current pointolite and the two balls are turned so that the line joining them is at right-angles to the axis of the system *L*₁, *L*₂. The image of one ball is formed upon the mirror *M*₁ and the image of the other on the mirror *M*₂. The normal to *M*₁ is very nearly parallel to the visual axis and the light reflected from this mirror gives horizontal and vertical (*H* and *V*) rotations as in the arrangement used by DITCHBURN and GINSBORG. Light from the mirror *M*₂ is reflected at the fixed mirror *M*₃ and reaches the drum camera. It enables records to be obtained

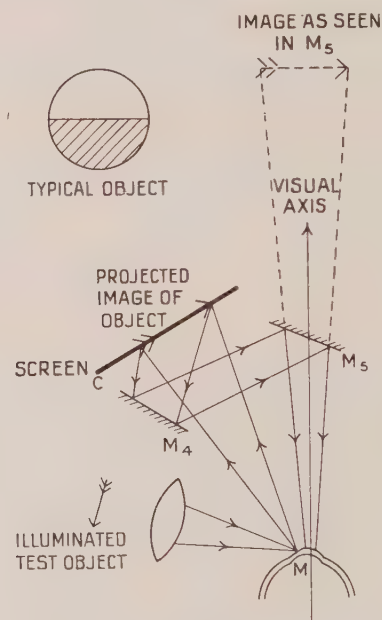


FIG. 3. — Apparatus for producing a stabilised retinal image.

of rotations (*T*) about the visual axis itself and also gives a second record of rotations in a horizontal plane. The contact lenses used are specially worked and made to fit the eye very tightly. It has been shown (DITCHBURN and GINSBORG [3] and RIGGS *et al.* [12]) that the contact lens follows the movements of the eye very accurately. The lens used by DITCHBURN and GINSBORG has the advantage that there is no interference with the subject's normal vision apart from the necessity of making him wear the contact lens. It may appear that the stalk, used in the apparatus as designed by FENDER, is a serious disadvantage since the lens will be moved every time the subject blinks. This disadvantage is, however, found in practice to be much less than might have been expected. It is found that within a very short time after a blink the contact lens returns accurately to an equilibrium position, but in most records the subject does not blink.

The apparatus used to produce a stabilised image is shown in figure 3. The optical system used before the mirror *M* is similar to that shown in figure 1 ex-

cept that the test object replaces the slits S_1 and S_2 . Light reflected from the mirror M is rotated through twice the angle by which the eye has rotated. It is therefore necessary to introduce an effective angular demagnification of a half in order to produce a retinal image which does not move when the eye rotates in its socket. A screen C replaces the drum camera previously used for recording but this is not viewed directly. It is seen by reflection in the mirrors M_4 , M_5 . When the total path from the eye to the screen C via the mirrors M_4 and M_5 is approximately twice the length of the direct path from the mirror M to the screen the angular movement of the image on the screen relative to the eye is zero. This adjustment may be checked if the eye is replaced by a telescope with a small plane mirror attached to its object glass. When the adjustment is correct the position of a point on the image with respect to the cross wires is unaffected by a small rotation of the telescope. When the contact lens shown in figure 1 is used it is possible to stabilise the image in respect of rotations about one axis only unless an anamorphic optical system is used in place of the mirrors M_4 and M_5 to introduce a demagnification of approximately 0.5 in a horizontal plane and 0.5 cosine 35° in a vertical plane. An optical system of this type was designed and used by the writer at Trinity College, Dublin with some success but the arrangement of the contact lens devised by FENDER (fig. 2) makes this complication unnecessary. Using a mirror with its plane perpendicular to the optic axis of the eye, the demagnification required is nearly the same in the two planes. It is only necessary to adjust the inclination of the screen a little to secure accurate stabilisation in both planes simultaneously.

The accuracy of measurement is shown by a section of a record obtained by FENDER (fig. 4). The sharpness on the trace is such that an angular rotation of 10 seconds of arc can be detected. Using a drum camera paper speed of 3.7 cm per second it is possible to

record a tremor whose speed is approximately 100 c.p.s. It is possible to stabilise sufficiently accurately to secure that the angular movement of the image with respect to the eye is much less than 1 % of the movement of the eye itself. If the eye were a solid optical system whose parts had an invariable relation to one another and if there were no accommodation this would mean that the stabilised image remained stationary upon the retina within 1 or 2 μ , that is to say within a distance which is small compared with the spacing between cones even where they are packed most closely. It is unlikely that changes in the shape of the eyeball (*e. g.*, in response to pulse movements) are sufficiently large or sufficiently rapid to interfere with the stabilisation in respect of tremor or flicks. A change in accommodation is the only likely source of trouble, for the visual axis is about 5° from the optic axis in a horizontal plane and a movement of the back nodal point of the eye by 0.02 mm will move the image 2 μ (an intercone distance) horizontally across the retina. Interference with stabilisation by this effect is minimised by using horizontal patterns. The fact that there are gross differences between vision with the stabilised and the unstabilised image shows that some degree of effective stabilisation is obtained. It is however desirable to repeat the experiments with observers who have little accommodation either from age or through the use of cyclopegics. This work is in progress

3. Records of eye-movements. — A typical record of eye-movements obtained by FENDER is shown in figure 4. The movements deduced from the records may be summarised as follows :

(a) Tremor of frequency 30-80 c.p.s. The amplitude of this tremor is 5-15 seconds of arc for the H and V rotation and up to 45 seconds of arc for the T rotation.

(b) Flicks occurring irregularly at intervals va-

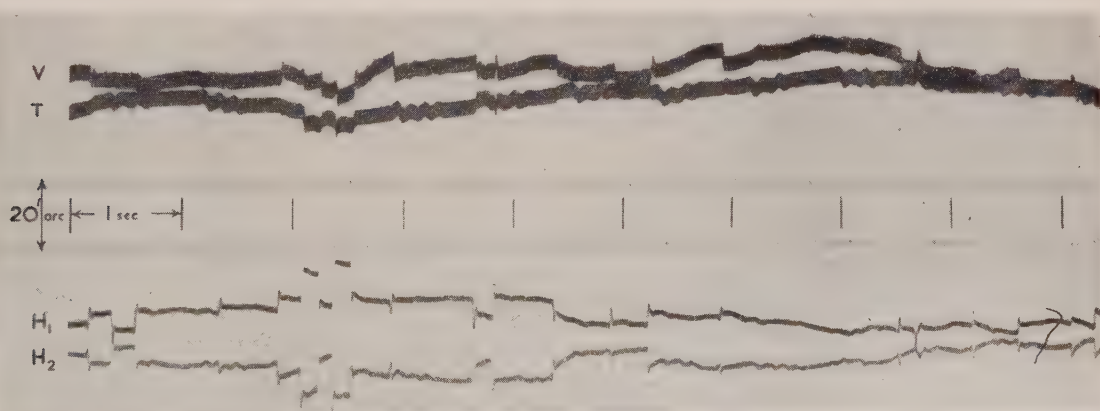


FIG. 4. — Record of Eye-movements (obtained by FENDER).
 H_1 and H_2 : horizontal movements (H_2 is reversed).
 V and T : vertical and torsional movements.
 Time interval marks 1 sec. Most records are taken at higher speeds.

rying from 0.03 second to 5.0 seconds. The amplitude of flicks for the H and V rotations ranges from 1 to 20 minutes of arc. For the T rotations the flicks are very small, usually about 2 minutes of arc.

(c) Slow drifts of up to 5 minutes of arc (for each rotation) occurring in the inter-flick periods.

It will be noticed that the torsional motion (T) of the eye ball is of the same nature as the other motions and differs only in magnitude. The torsional movements observed are very much greater than the « normal torsion » predicted by LISTING'S Law. The torsional movements are, however, too small to be of significance in relation to the theoretical discussion at the conclusion of this paper. They are being reported in detail in a paper by FENDER [5] and will therefore not be further discussed in this paper.

The maximum angular velocity during the tremor movements is about 20 minutes of arc per second. The angular velocity during the flick is of order 600 minutes of arc per second. The angular velocity during the drift movement is very small, being of order 1 minute of arc per second, but the total movement during a drift period is of the same order of magnitude as the movement during a flick because whereas the flick lasts a few hundredths of a second the mean time for a drift period is of order one second.

4. Movements of the image on the retina. — We have so far considered the movements in terms of angular rotations of the eye. Let us now consider the

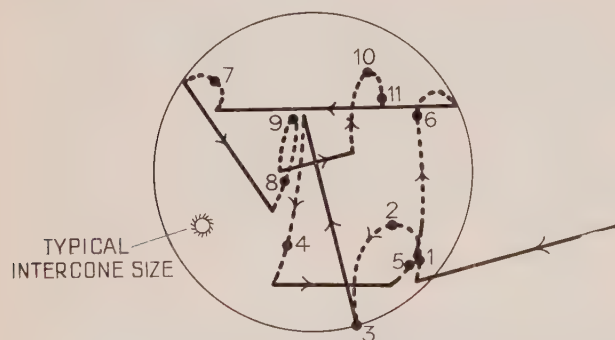


Fig. 5. — Movement of the image of a point object on the retina.

The large circle is of radius 25μ (5 min. arc). --- represents slow drifts, — represents rapid flicks. Numbered dots indicate order in which movements are made and are spaced at equal time intervals of 200 m sec. On this particular occasion the whole movement is within a 25μ radius circle but longer period records reveal movements within a circle of radius 50μ .

movements of a small point on the image across the retina. The excursion due to the tremor corresponds to a movement of between 1 and 3μ on the retina. This is about the same as the inter-cone distance in the centre of the retina. The total effect of the drifts and flicks operating together is to make the image of a point object wander around a small region whose diameter is about 100μ in the centre of the retina, i. e., somewhat smaller than the central territory defined

by POLYAK [9]. Detailed analysis (DITCHBURN and GINSBORG [4], shows that the drifts are random motions but that the flicks are corrective. That is to say when the image approaches the edge of this central region there is a tendency for a flick to occur towards the centre. Figure 5 shows the representation of a series of drifts and flicks expressed in terms of movements on the retina.

5. Relations of the movements to visual signals. —

It is possible to record the movements of both eyes simultaneously by additions to the apparatus shown in figures 1 and 2. A typical pair of 8 horizontal rotations are shown in figure 6. The drift and flick

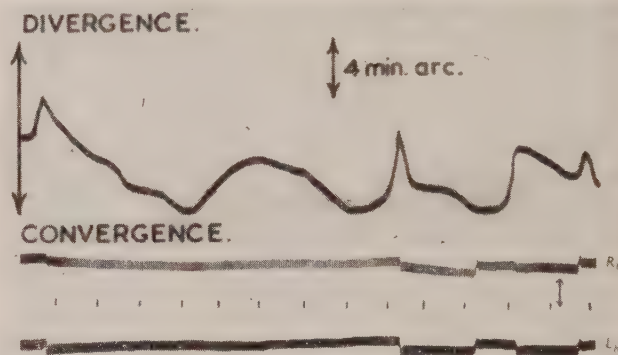


FIG. 6. — Binocular Horizontal Movements.

R_h : right eye ; L_h : Left eye.

Time interval marks 0.2 sec.

Vertical arrow represents 4 minutes of arc in upper part and 20 minutes of arc in lower part of figure.

The relative motion of the two eyes is shown on a larger vertical scale in the upper part of the figure.

movements occur in opposing directions in the two eyes so as to produce convergence/divergence waves as shown in the figure, even though the subject is gazing as steadily as possible at a point where distance is fixed. These may be related to the accommodation changes reported by ARNULF *et al.* [1].

In some experiments the whole of the corneal portion of one of the contact lenses was covered with an opaque film of rhodium and the movements of both eyes were recorded. The records show no significant difference from those obtained with binocular fixation. In some other experiments the fixation spot was extinguished after the apparatus had been aligned. The records obtained in these experiments show the three characteristic types of movement but the flicks and drifts are very much larger. The subject seemed slowly to lose the direction of fixation. In one further series of experiments the subject viewed a stabilised retinal image and it was found that his eye movements were then quite normal.

The first of the three sets of experiments mentioned in the preceding paragraph shows that the binocular fixation is not corrected by signals depending upon

disparity of the images received by the two eyes. The second shows that even in the absence of any visual signals a moderately good fixation is maintained for a short period, and that all the fixation movements still exist. The third shows that when the target spot is fixed independent of the movement of the eye the general fixation mechanism still operates. Taking these three results together we conclude that the maintenance of fixation depends not upon visual signals only but upon signals received from the proprioceptor muscles or on some signal which is not derived from the retina.

The following experiment appears to show that the eye is unable to see anything during the flick periods. The light reflected from the mirror on the contact lens is allowed to fall upon the edge of a photo-cell so that the movements cause signals to appear in the cell. The output is fed through a high pass filter into an amplifier whose response is poor at low frequencies. The output from the amplifier is displayed on a cathode ray oscillograph and the beam is displaced only when a flick occurs since the signals received from the drifting movements are of too low frequency to be amplified, and those received from the tremor are too weak to be noticed. It is found that the pips created by the flick movements of the eye are not seen by the subject although a second observer seated beside the subject is able to see them clearly. It appears at first that this effect may be due simply to the fact that the eye is moving so quickly during the flick that no one retinal receptor receives enough illumination to stimulate it. This is not so. The moving spot on the cathode ray oscillograph forms an image on the retina of the second observer. The rate of motion of this image is fast compared with the motion created by the flick of the eye and the second observer sees it. It therefore appears that some secondary mechanism is required to explain the inhibition of vision during the flick.

6. Vision with the stabilised image. — Figure 3 shows one type of object which has been used for observation with the stabilising system. A field of approximately 1° is divided horizontally, the lower half being 40 % as bright as the upper. It is found that initially the subject can see the line of division clearly but that after about 5 seconds the line of division vanishes and the whole field appears to be uniformly illuminated. This state persists for a short period and then suddenly normal vision is restored. After another short interval the line of division again vanishes, and so on. A second type of object has recently been studied by FENDER. It consists of a black bar of visual length 2° and visual width 8 minutes set on a light ground. It is found that after a short time the black area appears to be invaded from the edges by patches of light and is finally completely obliterated so that the whole field appears uniformly illuminated although no light is reaching a certain region of the retina. RATLIFF, RIGGS and co-workers [11]

have made a detailed study of the effect of stabilisation on the ease with which a black wire on a bright ground can be seen. They find that, with the stabilised image, the black line target is clearly seen when it first appears, but the line begins to fade out and finally disappears altogether. A wider line took longer to disappear and often reappeared from time to time during one minute of steady fixation. With an unstabilised image the fading did occur for fine lines but seldom for heavier lines. They modified the optical system so as to increase the rate of movement of the image across the retina instead of decreasing it and they found that under these conditions there was scarcely any disappearance of even very fine lines. Other experiments showed that the increased movements may be disadvantageous when flash exposures are used. A few experiments have been made with coloured patches of light. The results obtained with different subjects are not entirely in agreement. There appears a general tendency for colours to appear much desaturated.

7. Discussion. — The experiments so far reported show that involuntary eye-movements are of importance in relation to visual perception. They are not sufficiently extensive to enable us to deduce any detailed theory of how the eye-movements are effective. The following discussion of eye-movements in relation to electrophysiological experiments on the eye is offered as a working hypothesis, useful for planning future experiments.

It is known that visual signals from the retinal receptors reach the brain by means of electrical impulses transmitted along fibres of the optic nerve. HARTLINE [7] succeeded in picking up impulses from individual nerve fibres in the eye of the frog and he examined the effects of different conditions of illumination on these impulses. He distinguished three different types of nerve fibre. One gave a burst of impulses in rapid succession when the eye was suddenly illuminated and also a large burst when the illumination was removed. This type gave a slow succession of impulses in response to steady illumination. The second type of receptor gave responses only when the illumination started and ended. The third responded only when it was switched off. He also showed that strong bursts of impulses could be produced when a small spot of light was moved across the part of the retina which included the receptor attached to the nerve fibre under observation. Later work (summarised by GRANIT [6]) shows that, in general, the behaviour of the receptor and nerve-fibre system is more complicated than that found by HARTLINE. It appears, however, to be generally true that there is a weak response to steady illumination and a strong response to changes of illumination. Various types of indirect evidence make it probable that this last statement is true for the human eye, though the details of HARTLINE's results cannot be assumed to be applicable to the human eye.

The human eye gives some response to a steady uniform illumination received, for example, through the closed lids, but its ability to perceive *slow* changes in this illumination is weak. The perception of this illumination is presumably due to a slow succession of discharges as mentioned above. We may now consider the perception of an element of pattern. Suppose for simplicity that the field of view is divided into two areas, one dark and one light. If there were no eye-movements, weak signals would be received from the illuminated area and very weak signals (possibly « noise ») from the unilluminated area. The effect of the tremor is that a set of receptors near the boundary between the light and dark area are continually being strongly stimulated because for them the illumination is being changed about 80 times a second. They therefore send very strong bursts of impulses along the corresponding nerves and continually convey to the brain strong signals which generate the perception of the boundary line. If the tremor were the only movement, then when the subject fixated steadily in a given direction the same set of nerve fibres would be continuously under strong stimulation in this way, and it appears probable that they would accommodate and their effectiveness would fall. The effect of the drift is to carry the boundary, in a time of the order of one or two seconds, to a new set of receptors. The strong stimulation now comes from a new set of receptors whose nerve fibres have not accommodated. Since the movement is very slow the brain interprets the signals in terms of a steady pattern and the subject does not see a movement in the visual field. If this process were to go on too long the point of interest would drift out of the centre of the retina where the cones are mostly closely packed and where the visual acuity is highest. Therefore there must be a restorative mechanism to bring the point of interest back somewhere near the centre of the retina. This restorative mechanism is to be found in the flicks. It is, however, necessary to arrange that the subject does not see the pattern flicking every time this restorative mechanism comes into operation. There is therefore some inhibition imposed so that no vision is obtained during the flicks.

When the test object is illuminated for a short period, the on and off impulses are generated all over the illuminated region and they cause signals which lead to perception of pattern even when there are no eye-movements. For very short flashes it is an advantage to have the retinal image stationary during the flash, partly because this makes it possible to ensure that the critical part of the target always falls on the best part of the retina. For longer exposures the tremor produces extra on off impulses from the receptors on the edge of a dividing line in the pattern. These are additional to the on impulses received at the beginning and the off impulses received at the end of a flash and they assist the perception of fine detail. Thus the eye-movements become an advantage when the length of flash exceeds a time which is comparable

with the length of the initial burst of impulses given when the stimulus is switched on. HARTLINE [7] found that the burst of impulses given when the light is switched on lasted about 0.1 second. RIGGS *et al.* [11] find that the stationary image is best for exposures of 0.034 sec. and 0.11 sec. but rapidly becomes less good for exposures of 0.21 sec. The « exaggerated movement » condition is considerably the best for exposures of 0.47 sec. This is as we should expect if the above theory of the effect of eye-movements is correct.

The hypotheses put forward account for most of the observed results. It should however be pointed out that although it is proved that eye-movements affect visual perception, it is not proved that each of the three types of movement described in section 3, is effective. The tremor is of very much higher frequency than the flicker fusion frequency and may be totally ineffective. It may be an unavoidable « noise » effect due to temporary fatigue in groups of nerve fibres forming parts of the opposed muscles which hold the fixated eye on the target. Detailed experiments in which the different movements can be restored separately are in progress.

The above discussion of the effect of eye-movements is probably over-simplified even in relation to the central part of the retina where it is believed that individual nerve fibres correspond to single receptors. We need to allow for the fact that the brain in some way « fills in » a region such as the blind spot from which it receives no signals whatever, and for a variety of similar effects. In peripheral parts of the retina, the inter-connections of the receptors with the ganglion cells undoubtedly play an important part but consideration of these is not within the scope of the present paper.

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On foveal and peripheral interaction in binocular vision

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SUMMARY. — Contrast and increment thresholds were measured by the presentation of the test stimulus in one of the eyes, adapting fields of mutually different brightnesses and colours being incident in both eyes. No essential influence was found on threshold value under such stimulation of the non-measuring eye, the threshold being equal to the value appertaining to exclusive stimulation of the measuring eye. Periods of dominance of the various stimuli can under certain conditions easily be recognized. Measurements of increment thresholds under fluctuating illumination of the opposite eye at various moments during the light-dark cycle of such stimulation show a complex behaviour apparently due to a non-peripheral mechanism. Some suggestions are made as to a possible influence of attentional effects on such measurements.

SOMMAIRE. — Des mesures de contraste et d'augmentation du seuil ont été effectuées en appliquant des tests d'excitation à un seul œil, tandis que des champs d'adaptation de luminances et de couleurs différentes interviennent dans les deux yeux.

Cette excitation de l'œil inactif ne semble avoir aucune influence essentielle sur la valeur du seuil, qui reste égale à la valeur du seuil d'excitation de l'œil servant aux mesures.

On peut dans certains cas observer aisément des périodes où dominent certaines excitations (?).

Des mesures de l'augmentation du seuil sous l'influence d'un éclaircissement fluctuant sur l'œil inactif, à différents moments du cycle obscurité-clarté, montrent une complexité apparemment due à un mécanisme non périphérique.

Quelques suggestions sont faites sur l'influence probable de l'attention dans de telles mesures.

ZUSAMMENFASSUNG. — Während beiden Augen Felder von stetiger oder wechselnder Helligkeit und Farbe dargeboten werden, wird ein Prüfreiz nur einem Auge geboten und dabei Kontrast und Schwellwert gemessen. Es ergibt sich kein wesentlicher Einfluss auf den Schwellwert, wenn das andere Auge gereizt wird. Der Schwellwert hängt ausschliesslich von dem Reiz des gemessenen Auges ab. Perioden der Dominanz der verschiedenen Reize können unter gewissen Bedingungen leicht erkannt werden. Messungen der Schwellwerte während einer Flimmerreizung des anderen Auges zeigen ein sehr verwickeltes Verhalten. Die Möglichkeit von störenden Einflüssen auf solche Messungen werden diskutiert.

Introduction. — In the progress of a study of mutual interaction between different retinal areas the question arose whether such interaction occurs between the retinae of the two eyes. We had not in mind the self-evident merits of binocular vision like depth-perception by stereoscopic fusion or the enlargement of the visual field. We were interested in the possibility of affecting the visibility via the one eye by the stimulation of the opposite eye. Experiments by GRAHAM [1], CRAWFORD [2] and PIRENNE [3] on comparisons between monocular and binocular thresholds point to the independence of the perceptions by the two eyes. Their results point to the conclusion that binocular thresholds are only smaller by the improved chance of detection when two independent instruments are used instead of only one. Their studies refer to experiments in which both eyes are stimulated under identical conditions on corresponding parts of the retinae by equal test stimuli. In these conditions they found neither in the periphery nor for central vision any mutual summation or inhibition for threshold measurements. Because of some aspects of more or less everyday practice one is inclined to accept this conclusion also for cases in which stimulating conditions of the two eyes are different. For instance, trained subjects can easily use a monocular microscope without closing the non-observing eye. Efficiency and accuracy of their observations seem not to be affected by the arbitrary stimulation of this eye. GRAHAM [1], CRAWFORD [2] and PIRENNE's [3] conclusion is not corroborated by the experiments of

BARTLETT and GAGNÉ [4], COOK [5], CROZIER and HOLSWAY [6], SHAAD [7] and COLLIER [8]. All the latter authors claim that summation effects occur between the two eyes.

There are studies [9] about the resulting subjective brightness impression when the intensities of the stimulations of the eyes differ. It was found that the binocular brightness appearance under these conditions is intermediate between those for each eye separately, but does not equal the appearance of the arithmetic average of intensities applied to only one eye.

Some investigators [19] have reported on the possibility of colour mixture by binocular vision. Under certain conditions this is possible in the binocular field; for instance, a red impression in the one eye and a green in the other eye result in neutral or yellow. Evidently under these conditions interaction in binocular perception is more than a simple combination of the perceptions of either eye, but such interaction is restricted to the subjective appearance as to brightness and colour. We investigated whether or not it can be stated that threshold conditions for perception in the one eye are unaffected by any kind of stimulation of the opposite eye. As far as we know no complete check is reported in the literature. There are only a few incomplete studies [2, 11, 12, 13] available on the subject.

The experiments and their results. — Threshold problems refer to the detection of differences in brightness or colour by simultaneous comparison of test stimuli in different parts of the visual field or by

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successive comparison of stimuli at the same location. The first are referred to as contrast thresholds, the second are indicated as decrement or increment thresholds. We had at our disposal an experimental arrangement in which two concentric circular stimuli for each eye were available. Wavelengths, intensities, diameter and times of presentation could be varied independently for each of the four stimuli. We used spectral bands, 100 Å in width around 5 000 Å and 6 500 Å, foveal and 7° eccentric fixation. The arrangement was recently described in detail [12]. Artificial pupils 2 mm in diameter were used. Peripheral fixation of the eyes was realized with two small fixation lights, one for each eye separately. For foveal fixation, patterns of four lights were used situated on the corners of a square about 2° in size. A systematic report of the various cases studied by us is presented in what follows.

I. Contrast thresholds. — In the observer's right eye a red or green adapting field 10° in diameter was projected. A red or green test stimulus, for foveal vision 75 minutes of arc and for peripheral vision 5° in diameter, was added to the adapting field. Consequently eight combinations of colours for adapting field and test stimulus and centre of presentation were studied. For a few intensities of the field the intensity of the test flash required for just noticeability was determined. Provisions were made for a suitable time of adaptation to the actual conditions in order to obtain stable results. Afterwards experiments were made when a red or green field 10° in diameter was projected on the corresponding part of the opposite eye. One striking point which impresses the observer when making these experiments has to be mentioned in order to evaluate the results correctly. Especially when brightness of the field in the one eye becomes more dazzling than the field in the opposite eye (for instance ten times as high) and colours of the fields are different, a fluctuating phenomenon can be observed. This phenomenon is related to the subjective appearance in the visual field in which also the mutual movements of the axes of the eyes interfere. Because of the equal size of the fields (10° in diameter) in both eyes and the projection of these fields on corresponding parts of the retina — when the eyes are adequately fixated — they could be fused, but the observer never succeeded in having the fields continuously fused for any considerable time. The observer was conscious of intermittently discrete and different subjective appearances. Periods proved to be highly dependent on brightness values and colours, on central or peripheral fixation and on the attitude, attention and training of the observer.

After simple introspection the following general analysis of the appearances can be given :

Case 1. *Conscious perception is exclusively due to the stimulation of one of the eyes.* Whether the optical axes of the eyes are or are not in proper position for projection of the fields on corresponding parts of the retinae

can evidently not be recognized by the observer. The possibility of such dominance of one of the stimulations can easily be demonstrated by presenting different objects in the visual fields of each eye separately. Sometimes only the one or only the other object is seen.

Case 2. *Conscious perception is evidently due to the combination of stimulations of both eyes* when the absence of proper positioning of the axes for projection of the fields on corresponding parts of the retinae can be recognized by the observer.

Case 3. *Conscious perception must be due to the combined stimulation of both eyes when cases 1 and 2 do not occur.* The appearance is not equal to what the observer knows to be due to the exclusive stimulation of the one or the other eye separately, only in the case of sufficient difference between the aspects of these exclusive stimulations. Otherwise the observer cannot without further aids recognize whether a dominance as mentioned under case 1 occurs or whether case 3 is realized.

For example in one of our experimental conditions the following appearances alternated. When a red field in the one and a green field in the opposite eye was used, both fields 10° in diameter, only a red or only a green field was perceived when case 1 was active ; a decentred mutual position of a red and green field of equal size was recognized when case 2 was realized, in the overlapping part some yellowish colour dependent on the brightness values of the two fields being apparent ; during the remaining time one circular field yellowish in colour was perceived (case 3).

From our experiments we derive this conclusion : when contrast threshold conditions are fulfilled in the one eye, the test stimulus becomes intermittently invisible under stimulation of the opposite eye. Periods of invisibility seem only to occur when the latter stimulation is completely dominant as described under case 1. We checked the latter point by the introduction of the possibility for the observer to distinguish whether the measuring (right) eye was active or not. This was done by making the size of the adapting field in this eye smaller than the diameter of the field in the other eye. It was found that when these fields were 10 and 8° in diameter the test stimulus — being just or far above threshold under exclusive stimulation of the right (measuring) eye — was only actually invisible when the larger field in the left eye was exclusively perceived. As soon as the adapting field in the measuring eye interfered in the perception, the visibility of the target was recognized, regardless of colours, brightnesses and location on the retinae of fields and test stimulus.

In table I some of the results are presented in terms of the ratio between threshold energies of the test stimulus with and without the field in the opposite eye. The mean deviation in the settings of the threshold brightness was about 25 percent for our

TABLE I. — Contrast thresholds in the right eye for a steady red or green adapting field, 8° in diameter and a red or green steady test stimulus : 5° in diameter for peripheral and 1°15' for foveal vision. Red or green field, 10° in diameter in the left eye. Each threshold value obtained by averaging of 10 settings of each observer. The ratio is the average of the values for two observers.

| Field right | Field left | Ratio contrast thresholds right eye without and with left field | | | |
|----------------|----------------|---|-------|--------|-------|
| | | peripheral | | foveal | |
| | | red | green | red | green |
| — | red : 42 mla | 1.1 | 0.83 | 1.12 | 1.03 |
| — | 0.20 mla | 0.95 | 0.97 | 0.94 | 1.00 |
| red : 16 mla | 42 mla | 1.08 | 1.07 | 1.03 | 0.98 |
| 0.11 mla | 42 mla | 1.03 | 1.12 | 0.93 | 1.05 |
| 16 mla | 0.20 mla | 1.00 | 1.02 | 1.16 | 0.98 |
| 0.11 mla | 0.20 mla | 0.91 | 1.00 | 1.02 | 0.91 |
| green : 29 mla | 42 mla | 1.00 | 0.98 | 0.98 | 0.95 |
| 1.4 mla | 42 mla | 0.93 | 0.93 | 1.12 | 1.00 |
| 29 mla | 0.20 mla | 1.09 | 1.02 | 0.87 | 1.08 |
| 1.4 mla | 0.20 mla | 1.16 | 0.99 | 1.10 | 1.16 |
| — | green : 87 mla | 1.02 | 1.05 | 1.01 | 1.12 |
| — | 0.87 mla | 1.00 | 1.09 | 0.97 | 0.99 |
| 29 mla | 87 mla | 1.10 | 0.98 | 0.89 | 1.01 |
| 1.4 mla | 87 mla | 0.98 | 1.01 | 1.09 | 0.98 |
| 29 mla | 0.87 mla | 0.90 | 1.23 | 1.02 | 1.02 |
| 1.4 mla | 0.87 mla | 1.22 | 0.89 | 0.98 | 0.93 |
| 16 mla | 87 mla | 1.00 | 0.98 | 1.07 | 0.91 |
| 0.11 mla | 87 mla | 0.99 | 0.91 | 1.00 | 0.97 |
| 16 mla | 0.87 mla | 1.01 | 0.97 | 0.91 | 0.89 |
| 0.11 mla | 0.87 mla | 1.01 | 0.94 | 1.08 | 0.95 |

observers and almost independent of experimental conditions. The results only refer to the periods in which the non-measuring eye is not exclusively dominant. When such a distinction on the various aspects of the conscious perception was not made or could not be made by suitable geometrical mutual proportions of the stimuli, a highly irreproducible effect was introduced in the measurements. This effect originates from the possibility of a breakdown of an actual dominance of the non-measuring eye by a sufficiently large increase in brightness of the test stimulus and the subsequent visibility of the target. This high brightness of the test stimulus should be interpreted as a threshold measurement. The brightness for which such a breakdown could be realized was far from stable and could fluctuate over several log units. Also mutual movements of the axes of the eyes and other factors influenced the periods of dominance. Our conclusion does not hold for one evidently very special condition, namely, when stimulation in the non-measuring eye subtends exactly the corresponding area of the test stimulus in the right eye. This case was tested by making the field in the non-measuring eye 5° in diameter for peripheral measurements and 75 minutes of arc in the fovea, equal to the corresponding sizes of the test stimulus. Now when contrast threshold conditions were fulfilled in the right eye, the presence of the test stimulus could intermittently be detected under stimulation of the other eye. It occurred only when absence of proper positions of the axes of the eyes for fusion was recognized by the observer. Indeed when with proper position of the axes the cir-

cular adapting field 10° in diameter and one target 5° or 75 minutes in diameter centrally located on it, was perceived consciously, decision by the observer as to the origin of the central target was impossible. This situation could arise from a simple combination in the binocular field of adapting stimulus in the right eye and the field in the other eye, or from an active fusion of test stimulus with the latter field, or from complete dominance of the perception in the right eye. The only available clue for the detection of the presence of the test stimulus is to investigate whether a shift in colour or a change in brightness of the central part occurs when the test stimulus is presented intermittently to the observer. In practice, because of impossibility of a steady fixation of both axes, the coincident projections of test stimulus in the right eye and the field in the other eye will frequently break down and the test stimulus is subsequently detected merely by fulfilling threshold conditions necessary for the exclusive stimulation of the right eye. Of course the possible occurrence of this complicating factor of equal size of the test stimulus and of the field in the other eye is also more or less important when sizes are slightly different. Because of the impossibility of adequate fixation of the eye, it was not possible to make quantitative measurements when difference in size was varied.

II. Increment thresholds. — a) Under steady illumination of the opposite eye.

Again in the observer's right eye a red or green adapting field was projected. A red or green test flash lasting 0.01 second, for foveal vision 75 minutes of arc and for peripheral vision 5° in diameter, was added to the adapting field. Intensities of the test flash required for threshold visibility were determined. These thresholds were in terms of intensities for which the chance of observation was 60 percent. They were obtained by interpolation between measurements of frequencies of seeing neighbouring on the 60 percent value, each chance being determined by 20-50 repetitions of the test flash. Afterwards these measurements were repeated when a red or green adapting field 8° in diameter was projected on the corresponding part of the opposite retina. Of course, the fluctuating phenomenon as to the appearance of the conscious perception of the steadily illuminated fields in the two eyes was again observed. However, when measurements were only made in periods of non-dominance of the non-measuring eye, again no influence on threshold values was found whatever the colours, brightnesses and location on the retinae of fields and test stimulus. The results in table II only refer to these periods. Periods for measuring were again made distinguishable for the observer by using fields of different size, 8° in diameter in the right eye and 10° in the left. The brightness of the test flash required for a breakdown of dominance of the non-measuring left eye and subsequent visibility of the flash was now more or less reproducible and not very far above the value found for the other periods. The difference increased with increasing

brightness of the field in the left eye, resulting in a rise up to 2-4 times as high when compared with the threshold values in the other periods. Relatively, accuracy was still poor. The average deviation was about 150 percent for our observers in the dominance-periods of the left eye and about 25 percent for the other periods. We again met the special condition when the field in the left eye and the area of the flash were coincident. This case was tested with a circular field 5° in diameter for peripheral vision and 75 minutes of arc in the fovea similar to the area of the flash in the measuring right eye, the adapting field in this eye being 10° in diameter. Proper position of the axes of the eyes for projection of the flash exactly on the corresponding field of the left eye can easily be recognized by the observer by concentric position of the fields, but is hard to obtain, as such a coincidence must be obtained synchronously with the presentation of the flash. The actual measurements were very difficult because of these complicating factors. The results pointed to the conclusion that the facts are as before: for non-dominance of the left eye the flashes are detected when threshold conditions for exclusive stimulation of the right eye are fulfilled; breakdown of dominance can arise from flashes not more than 4 times as bright as the threshold value.

b) Under fluctuating illumination of the non-measuring eye.

In the previous section on contrast thresholds it was noticed that the procedure for threshold-measurements breaks down when geometrical conditions of the steady test stimulus are exactly copied on the corresponding area of the opposite retina by a steady suprathreshold stimulation. Consequently conditions as to geometry and time-distribution of these two stimuli were identical.

In line with this situation is — when applied to increment thresholds — the presentation of an abrupt suprathreshold change in brightness in the visual field of the left eye synchronously with the testflash on exactly the corresponding area of the right retina. When these conditions are fulfilled the observer cannot decide the origin of the change in apparent brightness in this part of the visual field. Of course, the possible occurrence of this condition is also more or less important when synchronism and identity in stimulated area of the retinae are not completely realized. We designed a set of experiments to study these special conditions in further detail. In the left eye a field 10° in diameter was presented intermittently, 1.5 second light 2.5 seconds dark. Red and green light was used. Experiments were made for central and foveal presentation. In the opposite eye a test flash was presented, lasting 0.03 second, at various moments of the light-dark cycle in the left eye. For the flash also red and green light was used. The flashes used in the experiments were 5° and 10° in diameter. The position of the flash — when adequate fixation was realized — was concentric with the field in the left eye. Intensity of the field was varied. In figure 1 we present a result

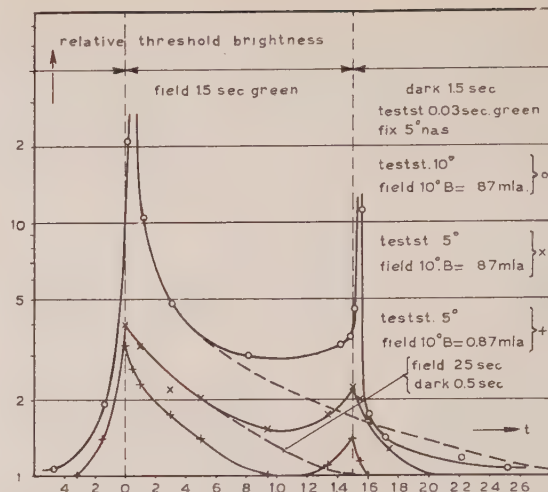


FIG. 1. — Relative threshold brightness for green flashes, lasting 0.03 second, 5° or 10° in size, measured peripherally 5° nasal in the one eye at various moments of the light-dark cycle in the other eye, which was stimulated intermittently by a green adapting field, 10° in diameter, on the corresponding part of the retina, brightness 0.87 and 87 mL.

typical for all conditions of centre of fixation and colours of the stimuli. The full curves are rather arbitrary and just an aid for easy inspection of the behaviour. The dotted curves only symbolize that if the initiation of the field stimulus should not be followed by an interruption, the threshold value would decrease to the original value appertaining to non-stimulation or steady illumination of the left eye (table II).

TABLE II. — Increment thresholds in the right eye for a steady red or green adapting field 8° in diameter and a red or green testflash 5° in diameter for peripheral and $1^\circ 15'$ for foveal vision. Red or green field 10° in diameter in the left eye.

Each threshold value obtained by averaging of 10 settings of each observer. The ratio is the average of the values for two observers.

| Field right | Field left | Ratio contrast thresholds right eye without and with left field | | | |
|----------------|--------------|---|-------|--------|-------|
| | | peripheral | | foveal | |
| | | red | green | red | green |
| — | red : 42 mla | 0.88 | 0.83 | 1.12 | 1.16 |
| — | 0.20 mla | 0.93 | 0.97 | 0.97 | 0.97 |
| red : 16 mla | 42 mla | 1.12 | 1.09 | 1.16 | 0.95 |
| 0.11 mla | 42 mla | 1.01 | 1.00 | 1.01 | 1.02 |
| 16 mla | 0.20 mla | 1.02 | 1.01 | 1.09 | 0.91 |
| 0.11 mla | 0.20 mla | 0.98 | 1.08 | 1.00 | 0.87 |
| green : 29 mla | 42 mla | 0.91 | 0.95 | 1.12 | 0.93 |
| 1.4 mla | 42 mla | 1.02 | 0.98 | 1.01 | 0.91 |
| 29 mla | 0.20 mla | 0.89 | 0.98 | 0.97 | 1.09 |
| 1.4 mla | 0.20 mla | 0.98 | 1.03 | 0.95 | 0.98 |
| — | 87 mla | 1.05 | 1.02 | 0.95 | 1.16 |
| — | 0.87 mla | 1.16 | 0.89 | 1.12 | 0.91 |
| 29 mla | 87 mla | 1.12 | 0.97 | 1.29 | 1.03 |
| 1.4 mla | 87 mla | 1.01 | 0.94 | 1.10 | 0.87 |
| 29 mla | 0.87 mla | 1.02 | 0.90 | 0.76 | 1.16 |
| 1.4 mla | 0.87 mla | 0.97 | 1.09 | 0.83 | 0.98 |
| 16 mla | 87 mla | 1.02 | 1.00 | 1.07 | 0.89 |
| 0.11 mla | 87 mla | 0.87 | 0.91 | 1.08 | 0.99 |
| 16 mla | 0.87 mla | 0.93 | 1.12 | 1.02 | 0.93 |
| 0.11 mla | 0.87 mla | 1.00 | 1.19 | 0.99 | 1.08 |

The interruption in the full-drawn curves at their highest values symbolizes the impossibility of measuring threshold values if proper position of the eyes could always be realized ideally and simultaneously with both test flash and intermissions or initiations of the field stimulus. The results point to the following conclusion: a sudden decrease or increase of brightness in the one eye affects the threshold measured on the corresponding part of the opposite retina when the test stimulus is flashing more or less simultaneously with such increase or decrease. It seems that sensitivity is decreased for some time around the moment at which brightness is changed.

Some of the other results are presented in the figures 2.

In the experiments previously reported on contrast and increment thresholds no adaptive effect was found for steady illumination. Only a rivalling phenomenon in dominance, an attention factor, between the various separate stimuli was apparent. No doubt such a phenomenon does not originate from a retinal mechanism.

Evidently the results described in this section also cannot originate from such a peripheral mechanism. Under the conditions of these experiments with fluctuating illumination of the left eye, the observer feels completely hypnotized by the events in the visual field. One is inclined to believe that a highly stable direction is given to various possible dominant factors, which would otherwise fluctuate at random, by the periodically intermittent illumination of both eyes. When periods of light or dark extend to more than about 3 seconds, at the end of such longer periods random fluctuation of such factors is again apparent. The data of the figures should show test stimulus-brightnesses for which, in the direction of possible dominant factors, conscious perception of the test-flash is involved.

It is far beyond our scope to present a critical expert discussion of such considerations. However, some of the remarks we made might be excused because of the highly interesting subjective appearances due to the dominances of the various factors we met when making our experiments.

In order to present matters in their simplest way we did not mention the difficulties in finding a suitable geometrical arrangement in the visual field for fixation aids and sizes of the fields in both eyes. In our first experiments we paid regard to the periods of dominance for the various conditions and consequently the necessity for the observer to distinguish between the periods in order to obtain a clear insight into the fluctuating visibility of the fields and the testflash. The final sizes and fixation aids mentioned were more or less suitable after a sufficiently long training period for detection of dominance periods when possible at all.

At first all experiments were made when the test stimulus was presented to the right eye. In the progress of the study the two observers acquired under these conditions a rather good ability in detection and analysis of the fluctuating phenomena as regards dominances. The period of investigation covered about

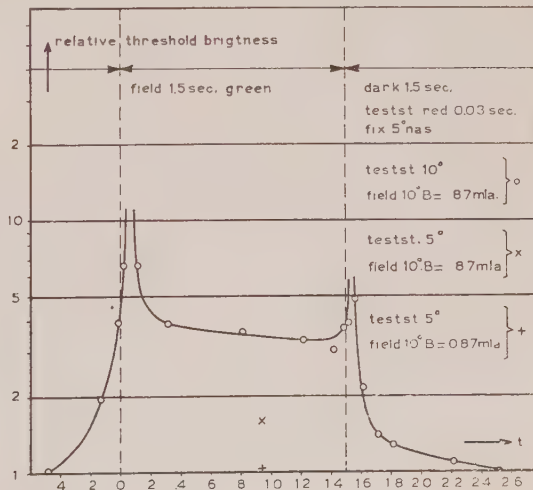
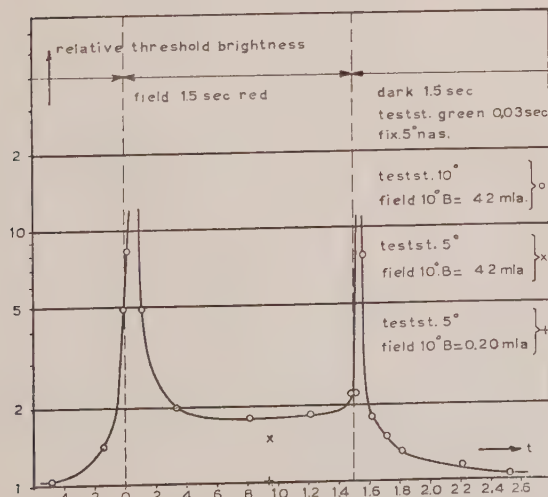
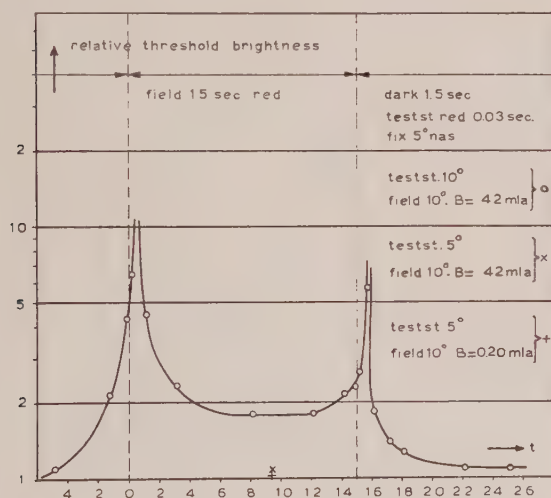


FIG. 2. — Similar data for other experimental conditions.

three months, at the end of which the tasks of right and left eye in the experiments were reversed. After a few sessions, at which the observers were more or less puzzled in making decisions on possible dominances, they recovered their good ability for such distinctions, the reported results on visibility of the test stimulus being still valid.

Discussion. — In the introduction to this paper we mentioned reports [1-10] on binocular and monocular thresholds. The findings with respect to the occurrence of binocular summation have not been unequivocal, positive and negative results having been found with about equal frequency. Such contradictory results are also found for other aspects of binocular interaction, such as the influence on the state of adaptation in the one eye by the stimulation of the opposite eye. CRAWFORD [2], IVANOFF [11], BOUMAN [12] and MANDELBAUM [13] reported the absence of an adaptive effect.

ELSBERG and SPOTNITZ [14] claim that such an effect should exist. If so, the visibility of a target via the one eye would also in all cases be affected by simultaneous stimulation of the other eye. In preliminary experiments BOUMAN [12] and MUELLER [15] found an inhibitory effect for higher brightness values of the adapting field. In the study of this present paper it was found that this inhibition does not appertain to certain periods in fluctuation of various possible dominant factors.

Probably such effects also interfered in the other contradictory results just mentioned and in the impossibility of binocular mixture of red and green to form yellow reported by HELMHOLTZ [16]. Others, however, have found that this mixture can easily be obtained.

Recent experiments of VERPLANCK, COLLIER and COTTON [17] have shown that successive responses to a repeated, invariant simple binocular visual stimulus are not independent. The probability of a «yes» (or a «no») response to any trial is associated with the responses to preceeding trials resulting in runs of «yes» or «no» responses. COLLIER [8] found evidence for a non-peripheral origin of this intertrial associative effect. The features of this effect are similar to the dominance-periods distinguished by our observers in the experiments reported here.

With regard to our results reported in the section on increment-thresholds for fluctuating illumination of the non-measuring eye, a few other studies should be mentioned. They refer to measurements of intensity-discrimination during the presentation of an adapting stimulus and at specified times following and preceding its onset and cessation all in the same eye. The experimental conditions are very similar to ours except that monocular vision is concerned. The typical result as to relative behaviour of ΔI is also similar to the data in figure 1. Primarily these effects were explored by CRAWFORD [18]. Subsequent investigations were made by BAKER [19] and BOYNTON and TRIEDMAN [20]. The latter included measurements of the b-wave

in the electroretinogram. The similarity in amplitude of the b-wave as a function of dark-adapting interval and the finding by HARTLINE and McDONALD [21] of a similar effect in the single optic nerve fibre of the horseshoe crab, led to suggestions as to a retinal mechanism for a thresholdrise just before cessation or initiation of the adapting fields and a subsequent drop into the dark — or light — adapting curve. The conclusiveness of the arguments for such a suggestion is destroyed by the results reported in this paper.

The following remark may be worth noting. The threshold value ΔI when measured monocularly or binocularly under normal conditions is evaluated by the observer as a just distinguishable brightness difference. From our measurements, when steady stimulating conditions of both eyes are different, it can be proved that the amount of energy supplied to one eye in order to detect a difference in brightness does not depend on the apparent brightness [4] in the binocular field. The required energy is still equal to the threshold value of the eye when this eye is exclusively stimulated.

In our investigation we were not concerned with pure colour contrast with elimination of brightness differences. Under all conditions a red or green test stimulus was added to a red or green adapting field in the eyes.

We are indebted to Mr P. ROEST for valuable assistance in the experiments and for his willingness to be an observer.

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The bleaching and regeneration of rhodopsin in the living eye of the albino rabbit and of man (*)

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SUMMARY. — 1. Two instruments are described by which the rhodopsin level can be measured in the living eye of the albino rabbit and of man.

- 2. The time course of bleaching and regeneration is plotted both for rabbit (fig. 4 & 5) and man (fig. 7 & 9).
- 3. The substance bleached in the rabbit has a difference spectrum similar to that of rhodopsin (fig. 3).
- 4. The substance bleached in man has a retinal distribution similar to that of rod density (fig. 8).
- 5. There seems little justification for using scotopic sensitivity as a measure of rhodopsin density.

SOMMAIRE. — 1. Description de deux instruments permettant d'étudier la transformation de la rhodopsine dans l'œil vivant du lapin albinos et de l'homme.

- 2. La durée de la décomposition et de la régénération est représentée sur des graphiques, pour le lapin (fig. 4 et 5) et pour l'homme (fig. 7 et 9).
- 3. La substance décomposée, chez le lapin, présente une différence spectrale analogue à celle de la rhodopsine (fig. 3).
- 4. La substance décomposée, chez l'homme, présente une distribution rétinienne analogue à celle de la densité des bâtonnets (fig. 8).
- 5. Il semble peu justifiable d'utiliser la sensibilité scotopique comme mesure de la densité de la rhodopsine.

ZUSAMMENFASSUNG. — 1. Es werden zwei Instrumente beschrieben, mit denen der Rhodopsin-Spiegel im lebenden Auge des Albino-Kaninchen und des Menschen gemessen werden kann.

- 2. Der zeitliche Ablauf des Ausbleichens und der Regeneration ist für das Kaninchen in den Abbildungen 4 und 5 und für den Menschen in den Abbildungen 7 und 9 dargestellt.
- 3. Die gebleichte Substanz beim Kaninchenauge hat ein Absorptionsspektrum ähnlich dem des Rhodopsins.
- 4. Die gebleichte Substanz ist beim Menschen in der Netzhaut ähnlich verteilt wie die Dichte der Stäbchen.
- 5. Es scheint nur wenig berechtigt die Dunkelempfindlichkeit als Mass für den Rhodopsingehalt zu benutzen.

Introduction

The importance of rhodopsin in the visual mechanism has been recognised ever since its discovery by BOLL [5], and a great deal of our present knowledge about bleaching and regeneration was already established by KÜHNE [16, 17] in the retinas of frogs and many other animals. Rhodopsin was seen to be contained in the outer segments of the rods of dark adapted retinas and never seen anywhere else in nature. It was therefore believed to be associated with rod vision. Meanwhile SCHULTZ, v. KRIES and PARINAUD firmly laid the foundations for the Duplicity Theory. From the comparative anatomy of the retinas of day and night animals, and the regional anatomy of the human retina it was established that cones cannot

opérate in very dim light ; for in these circumstances only rods possess the requisite sensitivity. The conclusion followed that rhodopsin is the photo-pigment of twilight vision.

If that were true the spectral sensitivity for twilight vision (the scotopic visibility curve) should be the same as the absorption spectrum of rhodopsin or as its action spectrum (i. e. the efficacy of bleaching). Comparisons of these spectral curves (LYTHGOE [18], WALD [28], CHASE & HAIG [8], SCHNEIDER, GOODEVE & LYTHGOE [26], WALD [29], CRAWFORD [9]), have shown an almost embarrassing agreement so, that there can be very little doubt that the first step in the scotopic vision of man and other mammals is the absorption of light by rhodopsin.

Since the rhodopsin of the rods will bleach in strong light and will regenerate in the dark, it might be expected that after light adaptation, the visual threshold

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would rise as a result of the smaller fraction of the incident light effectively absorbed. The enormous changes of sensitivity which occur in light and dark adaptation have often been explained in terms of this possible mechanism, despite the rather improbable quantities involved. But although the scotopic threshold (or its logarithm!) has frequently been used as a direct measure of the quantity of rhodopsin present in the human eye, very little attempt has been made to justify this far-reaching assumption, and where investigation has been made, the results have not been reassuring.

GRANIT *et al* [13, 14] measured the scotopic sensitivity of an animal (frog, cat) by the electroretinogram and found that after light adaptation the size of the electric wave, so far from going hand in hand with rhodopsin regeneration, did not begin to increase until the pigment had regenerated to 50 % of its full dark adapted value. BAUMGARDT [4] calculated that at moderate illuminations which produce a considerable sensitivity change, extremely little rhodopsin can be broken down.

RUSHTON & COHEN [23] verified this directly by using the relation that the *percentage* of rhodopsin bleached by a given exposure is independent of the actual rhodopsin density (assumed small). If the retinal illumination is known in scotopic units, the percentage bleaching may be calculated from DARTNALL, GOODEVE & LYTGOE's [10] results upon the bleaching rate of frog's rhodopsin. Alternatively a rhodopsin solution may be substituted for the human eye, and the percentage bleached in the exposure directly measured, with appropriate geometrical corrections. Both these estimates were in fact made (only the first was published) and agreed in showing that the brief illumination used could not at most have bleached more than 2 % of the retinal rhodopsin. But instead of the threshold changing 2 % it changed at least 20 times. Since the test light was 3' in diameter and lasted 7 msec, changes in summation area or summation time could not contribute in any simple fashion to this result. WALD immediately repeated this experiment [30] with essentially the same result.

In order, however, to have clear knowledge as to how visual function is related to the density of retinal rhodopsin we need really to be able to measure this directly. Nearly the only method employed has been to kill the animal, dissect out the retina in red or dim yellow light, and estimate in some way the rhodopsin present. KÜHNE simply observed the colour quickly in diffuse daylight, FRIDERICIA & HOLM [12] compared the excised retinas with GARTEN's colour charts, TANSLEY [27] extracted the rhodopsin into a clear solution of digitonin and measured the density photographically, and ZEWI [32] and PESKIN [20] used photocells to measure their solutions. There are great disadvantages to this type of investigation. An animal can only supply a single measurement (or at most one measurement from each eye), and a whole series of such measurements is necessary before the

results can be related to visual function. It is very hard moreover to obtain a set of comparable animals comparably dissected and extracted in the very poor lighting conditions which are essential to avoid post-mortem bleaching. The prohibitive care and labour required to follow the rhodopsin levels through any simple manœuvre in light and darkness is reflected in the fact that only one relation appears ever to have been attempted, namely, the regeneration of rhodopsin in the dark after more or less complete bleaching.

A method which allowed rhodopsin (or porphyropsin) to be observed in the living eye was used by ABELSDORFF [1, 2]. He looked through an ophthalmoscope into the eyes of crocodiles and certain fish which have a white tapetum and observed a purple pigment which could be bleached locally by a strong light focussed on a limited area. He made no attempt at quantitative measurement in these animals, and he considered the method impracticable with mammals. But BRINDLEY & WILLMER [6] applied this principle with partial success in man. They divided a monochromatic beam so that part filled the pupil and part traversed a comparison pathway including a photometric wedge. The light returning after reflexion at the *fundus oculi* was matched with the comparison beam (reflected at a roof-prism) and the appropriate wedge setting read for various wave lengths of light.

In order to make a match it was necessary to use a light so strong that the rhodopsin was rapidly bleached, thus their actual measures are not very reliable. But one of us was encouraged by this work to build the retinal densitometer [24] which he had earlier designed, and this has proved a useful instrument with which to follow the rhodopsin level in the living eye of the albino rabbit in various conditions of illumination.

Part I: MEASUREMENTS IN THE RABBIT

The Retinal Densitometer

(a) *Principle*: In principle the rhodopsin was measured by the ophthalmoscopic method of ABELSDORFF, and of BRINDLEY & WILLMER. The light was shone into the eye, and the fraction reflected back was determined. Changes in rhodopsin density must produce a small change in the back-reflected fraction of the light, and the problem was to eliminate all the other factors which might disturb the determination of this fraction. Since the light used for measuring must not rapidly bleach the rhodopsin being measured, the signal is necessarily small and the back-reflected light must not be wasted. On the other hand not all this light comes from the retina, and corneal and other unwanted reflexions must be removed as far as possible.

It is not easy to hold the intensity of a light exactly constant nor the amplified output of a photocell quite steady over the space of several hours, so it is impor-

tant that small fluctuations in these quantities should not be interpreted as changes in the density of rhodopsin. The densitometer designed to satisfy as far as possible these requirements is shown in figure 1.

(b) *Optics* : The light source, S, was a 6 V, 36 W tungsten car headlight bulb run from a 6 V car battery (simultaneously charged from a rectifier). The light was collimated by the lens L_1 , passed through a "monochromatic" interference filter F, and fell upon the plate G_1 at the polarising angle. The reflected ray, which was completely plane-polarized, was focussed by L_2 through an artificial pupil upon the cornea, and illuminated a circular patch of retina. Some of the back-reflected light is transmitted

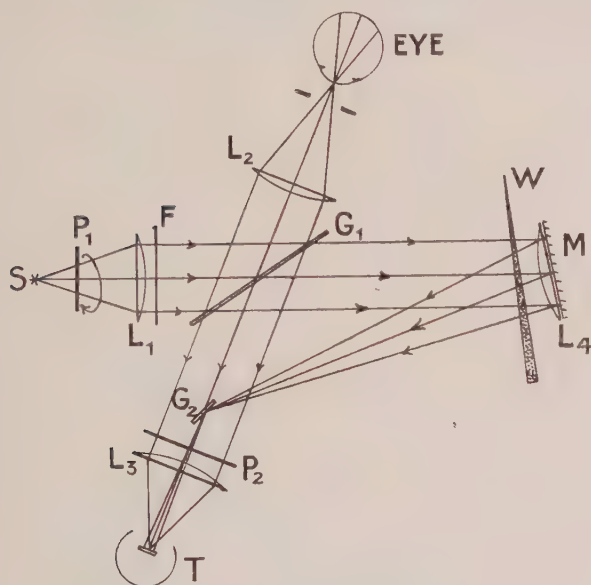


FIG. 1. — The retinal densitometer : optical arrangement.

through the glass plate G_1 , and is focussed by L_3 upon the cathode of a photomultiplier Tube T. Now most of the unwanted light is reflected from the cornea and L_2 and hence is plane-polarized, so it may be removed by introducing a polaroid P_2 suitably orientated. The light scattered back from behind the retina, on the other hand, is depolarized, and so half of it is in the sense to pass P_2 ; to this half the glass G_1 is perfectly transparent.

In order to make the necessary measurement independent of drifts in the intensity of light source or of photocell amplification, comparison is made with a second light beam which, passing through G_1 , is reflected at the mirror M, and glass plate G_2 (upon which it is focussed by L_4) and so into the photocell. A convenient way of making the comparison is to place a rotating polaroid P_1 , in front of the light source S. If P_1 is slowly rotated, a position (zero) will be found where no light is reflected from G_1 into the eye. At an angle θ from that position the light reflected into the eye will be proportional to $\sin^2 \theta$. Thus the light received by the photocell will be $\sin^2 \theta$

from the eye together with the contribution from the comparison path. This latter will be the component of the light through P_1 which is in the plane admitted by P_2 , and will have the value $b \cos^2 \theta$, where the value b will naturally depend upon the position of the wedge W. The total light received by the photocell will thus be

$$I = a \sin^2 \theta + b \cos^2 \theta$$

and by moving the wedge so that a and b are equal we get

$$I = a (\sin^2 \theta + \cos^2 \theta) \equiv a$$

and is independent of the position θ .

The output of the photocell is condenser-coupled to an oscilloscope, and, as the polaroid P_1 rotates at some 40 rev/sec, an 80 cycle A. C. is in general seen on the screen. By moving the wedge, the amplitude of the sine wave may be brought to zero and in this case

$$a = b.$$

Any change in the rhodopsin density of the eye will change a and upset the balance. This is restored by an equal change in b . Since the light passes twice through the retina and twice through the wedge, the change in rhodopsin density is measured directly by the change in wedge density.

It will be clear that though the balance is sensitive to changes in a it is not affected by a change in the intensity of the light source or the gain of the phototube, for though the photo-electric output depends upon these things, it is not the output that is measured, but simply the wedge setting required for the output to have zero A. C. component; and the fact that we are concerned only with 80 cycles A. C. avoids all difficulties with D. C. stability.

(c) *Signal "Noise"* : If bright light can be used, it is easy to set the wedge to give zero amplitude to

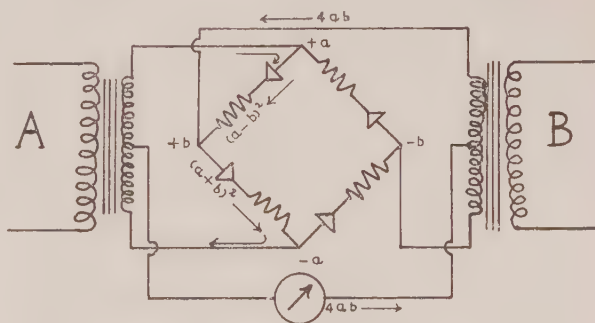


FIG. 2. — Phase-sensitive rectifier bridge for integrating the product of two inputs A, B.

the A. C. signal. But with weak lights and large amplification of signal it was difficult to set the zero accurately in the presence of the inevitable "noise". A very great improvement was achieved through the use of the elegant arrangement indicated in figure 2 for which we are indebted to Mr M. RYLE, F. R. S., of Trinity College, Cambridge.

B is the amplified output from the phototube T . A is a large sine wave input in phase with the signal to the eye, obtained by deflecting a portion of the beam into a second photomultiplier tube. The A. C. components of both inputs are transformer-coupled to the rectifier bridge.

In each arm of the bridge the current is roughly proportional to the square of the voltage difference, and the total effect is that the signals A and B are multiplied together and the galvanometer integrates the result.

Suppose the signal A is $a \sin pt$, and B is $b \sin qt$, then as is well known

$$\int_0^{2\pi} a \sin pt \cdot b \sin qt \cdot dt = 0$$

for all values of p except the value $p = q$.

So the galvanometer integrates to zero all the Fourier components of the noise in the signal B except that small fraction which has both the same period as the incident sine wave and is more or less in phase with it.

By using this circuit, the retinal densitometer will measure changes of density correct to $0.002 \log_{10}$ unit. Each reading takes about 5 sec to perform, and the light employed causes a change of less than 0.0002 unit of rhodopsin density. Since the maximum density in an albino rabbit's eye lies between 0.1 and 0.15 the densitometer has a speed and accuracy adequate for many purposes.

The experiment

The first experiments were made by BRINDLEY and RUSHTON [22] and the work was developed by HAGINS and RUSHTON [15].

The experimental procedure in general is as follows. The rabbit is decerebrated under ether and left to recover from the anaesthetic, sufficient urethane being given to keep it quiet. The head is fixed, the pupil kept fully dilated, and when necessary the eyelids are held open by threads. Most rabbits have a very bad optical surface at the cornea, but with the aid of a contact glass, a reasonable image of the retina was formed in the neighbourhood of the glass plate G_1 , figure 1.

By viewing this it was thus possible to arrange that the region of retina investigated was that part, below the horizontal line of nerve fibres, which as KÜHNE observed is especially rich in rhodopsin.

It could also be verified that the eye was centred so that the iris was not visible through the artificial pupil and there were no serious stray reflexions.

The results

The details of our experiments with decerebrate rabbits and also with excised eyes mounted in a bath at various temperatures are appearing elsewhere. The

results now to be presented are some fresh observations from a single experiment designed to substantiate the claim that rhodopsin is in fact being measured, to illustrate the precision of the method and to display the course of bleaching and dark-regeneration.

The animal was first fully dark adapted. Then the density of the retina was measured in monochromatic light at 10 different wave lengths by interposing the interference filters in turn. Next a bright green light was shone into the eye and the density measured every 15 or 30 sec to give the time course of bleaching (fig. 4). The density was then measured again at various wave lengths, and finally the regeneration in the dark was followed (fig. 5).

The measurements clearly show that the optical density becomes less in strong light and increases

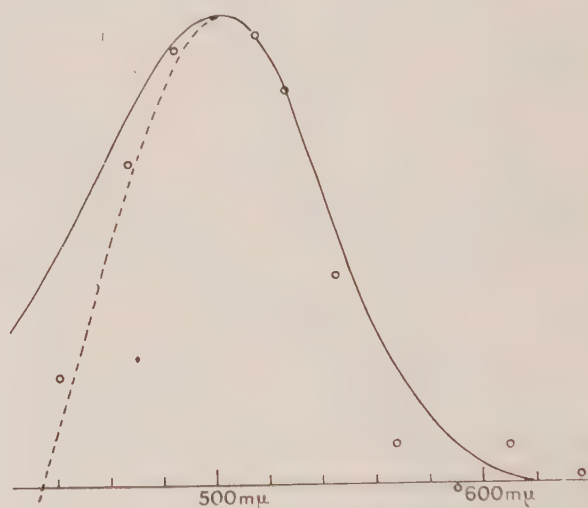


FIG. 3. — Full curve : absorption spectrum of rhodopsin. Broken curve : difference spectrum of rhodopsin at p_H 5.5. Circles : difference spectrum of retinal bleaching.

again in the dark. The important thing is to know what is the difference spectrum of the pigment (or whatever it is) which thus bleaches and regenerates. This spectrum may be found at once from the two sets of density measurements obtained before and after bleaching; for at each wave length the difference of the wedge settings must give the change in density of the pigment which was first present and subsequently bleached. In figure 3 the circles show these differences plotted against wavelength, and the full and broken curves are the well known absorption spectrum and difference spectrum of rhodopsin in solution (from WALD). Without entering into the finer points of comparison or making the corrections necessary for any exact analysis of the bleaching we may say that the circles fit the curve.

We thus conclude that it is rhodopsin that we measure because in the part of the rabbit's retina which Kühne found to be richest in rhodopsin there is a loss in the light and a slow return in the dark of some-

thing which has a difference spectrum similar to that of rhodopsin.

Figure 4 shows the time-course of bleaching with bright green light of wave length 517 m μ . The retinal illumination was about 4×10^{14} quanta cm $^{-2}$ sec $^{-1}$. It would be expected that the fall in density should at first be rapid and later slower, for, with an initial density of 0.12, about 25 % of the light incident upon the retina will be absorbed by rhodopsin, whereas later on, the retina will be nearly transparent. The points do not, however, fall upon the theoretical curve calculated from this simple consideration; after some minutes the density falls a good deal too slowly. This

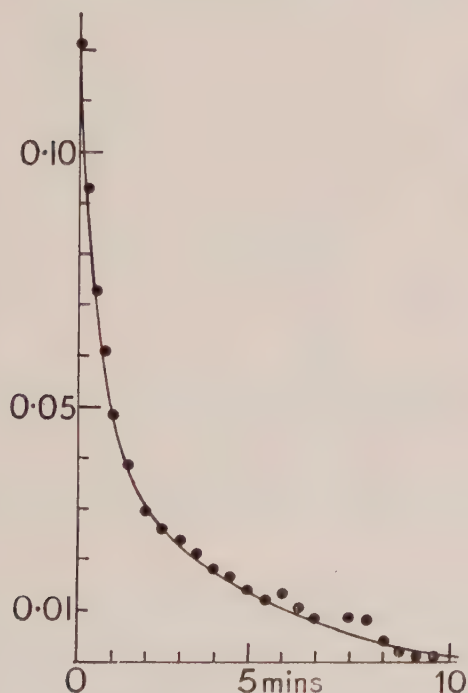


FIG. 4. — Time course of bleaching in the rabbit's eye. Ordinates: retinal density in excess of the fully bleached value. Curve drawn free-hand through points.

is presumably due to the accumulation of photoproducts and the onset of rhodopsin regeneration which only slowly reach equilibrium.

The course of regeneration in the dark is seen in figure 5. The measurements were made in rather weak light (10^{13} quanta cm $^{-2}$ sec $^{-1}$) of wave length 517 m μ applied for about 5 sec every 5 min. After 90 min. when regeneration was complete, the measuring light was turned on and left on (at the point indicated by the arrow in figure 5). The subsequent curve shows the rate of bleaching produced from which it appears that each 5 sec measurement bleached less than 0.0002 density unit of rhodopsin.

The regeneration curve shows features which have already been reported (HAGINS & RUSHTON [15]). It takes some 80 min to reach completion and the first half proceeds at a uniform speed. This linear rise was

found by ZEWEI [32] in the frog and by us and by WEALE [31] in the cat, but not by TANSLEY [27] in the rat, nor does it seem to occur in man, as will appear in Part 2 of this paper.

The density of rhodopsin is a great deal higher than might have been anticipated from a superficial consideration of the published measurements on extracted rhodopsin. The value in figure 5 is an extinction of 0.17 corresponding to 32 % absorption of the incident light. WALD's [28] figures for the rabbit, for instance, are 0.019 extinction and 4.2 % absorption. As he pointed out, the formal assumption of a uniform rhodopsin layer spread uniformly over the retina is bound to give a figure considerably lower than the actual density in the rods, and he estimated that the value should be doubled [28] or even multiplied by 5 [30].

That part of the discrepancy which is due to the reti-

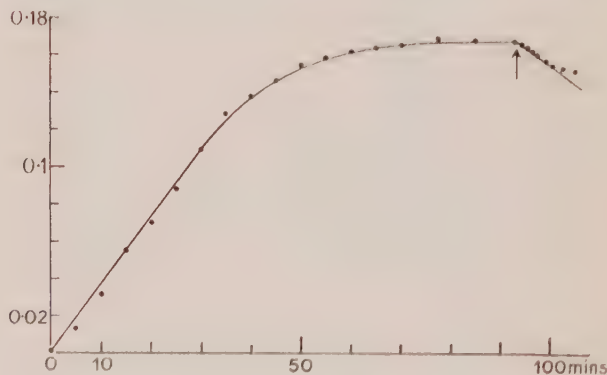


FIG. 5. — Time course of regeneration in the rabbit's eye. Ordinates: retinal density in excess of the fully bleached value. At the arrow the measuring light was left on instead of shining for only 5 sec once every 5 min.

nal area containing elements other than rods is likely to affect our measurements in much the same way as WALD's. The higher rhodopsin value we obtain is chiefly due to our selecting for measurement that particular region of the rabbit's retina where the density is exceptionally great. There is, in addition, the fact that the rhodopsin molecules in the rods are orientated perpendicular ly to the axis (SCHMIDT [25], DENTON [11]). This increases by 50 % the chance of their absorbing light passing axially down the rods, and hence rhodopsin density in the rods should be 1.5 time as great as that estimated directly from the random orientation in solutions.

Part II: MEASUREMENTS IN MAN

The Rhodopsinometer

The difficulties in applying the foregoing method to measurements in man result chiefly from the black pigment which everywhere lines the retina. On this account only a minute fraction of the blue-green mea-

suring light is reflected back, so that unwanted reflexions and scatter become very serious. Also when the eye is measured against a separate comparison beam, the smallest head and eye movements alter the readings.

It was therefore decided to compare the densities in orange and blue-green light sent in succession along the *same* optical path. This eliminates to a first order small eye movements but imposes a fixed wave length for the measuring light. The rhodopsinometer used is shown in figure 6.

A narrow beam of light (5°) is focussed onto the cornea through a hole in the silvering of a cover-slip, and the light reflected back from behind the retina passes out through the dilated pupil, is reflec-

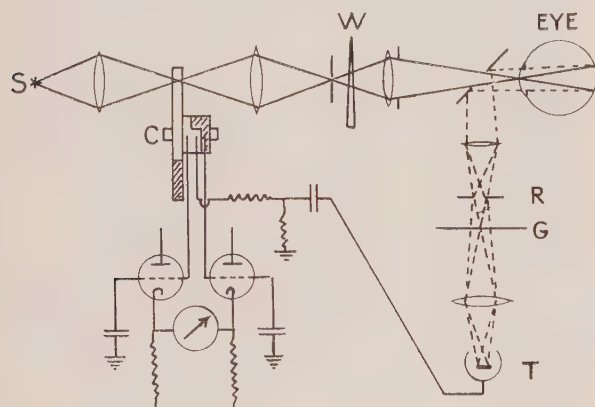


FIG. 6. — The rhodopsinometer: optical and electrical arrangement.

ted at the mirror and focussed upon the cathode of a photomultiplier tube T. R is a variable stop in the retinal image plane, adjusted to view only the centre of the illuminated patch of retina. In certain positions of the eye a corneal reflexion appeared. This came to a point focus in the plane of the glass plate G, and was stopped by a tiny piece of plasticene appropriately placed.

Now between the light source and the eye is placed a transparent wheel C one half of which is coloured blue-green and the other half orange, so when it rotates (at some 20 rev/sec) these two colours are alternately presented to the eye. In general the output from the photocell will be different for the two half-cycles, but this difference may be abolished by shifting the purple wedge W in the incident light beam, since this will strongly affect the blue-green transmission, but only slightly the orange. The signal-to-noise ratio is much improved by the commutator arrangement on the axis of the colour wheel which directs the green output into one integrating condenser and the orange into another. Equality is detected by the null reading of the galvanometer connecting the two cathode followers, and the wedge setting will be independent of small variations in the brightness of the light source, or amplification of the

photomultiplier. On the other hand any bleaching of rhodopsin will upset the balance and to restore it, as much "purple" must be added in the wedge as was lost in the rhodopsin. Change in retinal rhodopsin is thus directly measured by reading the change in position of the purple wedge.

The results

Two short notes of our results have already appeared (CAMPBELL & RUSHTON [7], RUSHTON & CAMPBELL [24]), and a more detailed analysis of the work will be published shortly. The results given

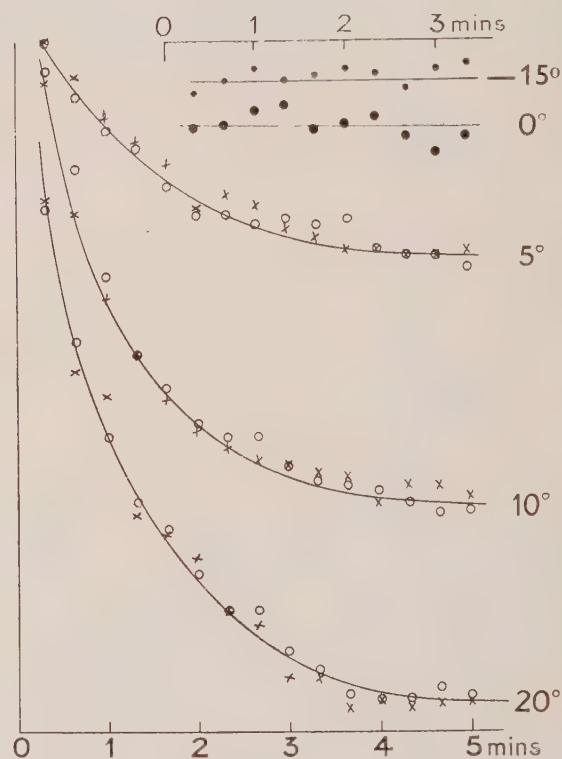


FIG. 7. — Time course of bleaching in man at 5 different retinal locations on the horizontal meridian. e. g. "20°" is 20° temporal to the fovea: "— 15°" is on the optic disc. Circles and crosses are two measurements repeated at 3 days interval. Ordinates: change of purple wedge setting.

here simply present the grounds for our belief that rhodopsin changes in the human eye can be measured by the rhodopsinometer with speed and accuracy.

Figure 7 shows the change which occurs when the dark adapted human eye is bleached. Measurements were made upon a small patch of retina 2° in diameter situated a distance temporal to the fovea which is indicated for each curve. The 20° curve for instance falls rapidly and exponentially in a fashion similar to rhodopsin bleaching in the rabbit (fig. 4). If this *does* represent rhodopsin bleaching in man we should expect none of it upon the fovea and optic disc where there is no rhodopsin. This is seen to be the case, for

the density at the fovea (0°) and the disc (-15°) does not change with "bleaching" (1).

Each region of the retina is seen to have a characteristic bleaching curve, and it is clear from figure 7 that the difference between the curves for 5° , 10° , 20° is far greater than between the circles and crosses on the same curve which represents a repetition of the measurements upon the same subject another day. A measure of the rhodopsin density of different regions of the retina is given by the total change in level of the curves of figure 7, the difference between the dark adapted and light adapted retinal density.

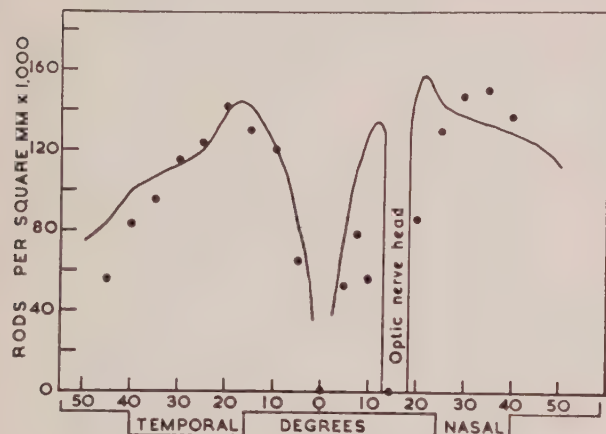


FIG. 8. — Black circles : measurements of rhodopsin density at the points shown along the horizontal meridian of the retina in man. Curve : ØSTERBERG's plot of rod density per mm^2 in the same region.

This measurement was made systematically for a number of 2° patches along the horizontal meridian from 45° temporal to 40° nasal, and the results are shown as dots in figure 8. The curve is ØSTERBERG's [19] histological determination of rod density over the same region of the human eye. There is clearly some correlation between rod density and what we claim is rhodopsin density.

Figure 9 shows the course of regeneration of rhodopsin in the dark together with an exponential curve of half-return period 7 min. Man thus differs in some respects from decerebrate and part-anaesthetized rabbits (fig. 5) and in others from normal rats (TANSLEY [27]), but discussion at this stage would be premature.

We think that what we measure in the human eye is rhodopsin because

(a) it is measured by the instrument designed to measure rhodopsin ;

(b) it is bleached by light in a manner very similar to the way rhodopsin is bleached in the eye of the rabbit ;

(1) Note : the curves of figure 7 have been shifted vertically for clearness. Only the shape of each curve, not its vertical position is significant.

(c) it regenerates again slowly in the dark taking half-an hour to approach completion ;

(d) it is absent at the fovea and optic disc, and elsewhere in the retina the density follows more or less ØSTERBERG's plot of rod concentration.

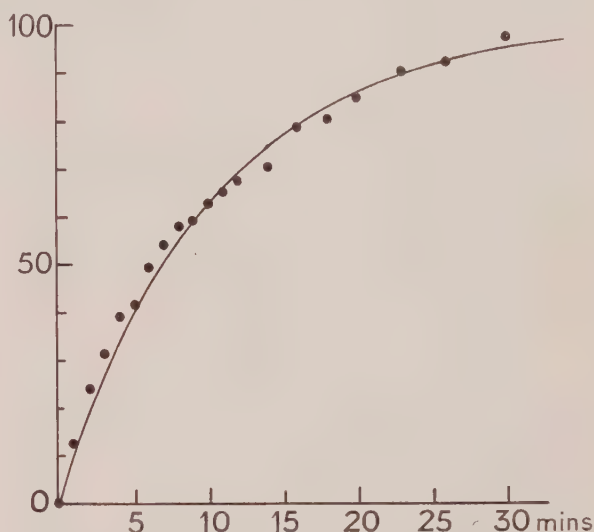


FIG. 9. — Black circles : time course of regeneration in man. Ordinates : percent fully regenerated. The curve is an exponential with half-return period of 7 min.

Discussion

The preliminary experiments here described throw some light upon the topic with which this paper opened, namely, the relation between rhodopsin density scotopic sensitivity.

Both in the rabbit and in man a bright light will bleach away rhodopsin, and a brighter light will do so faster. Regeneration follows in the dark. In one sense there seems a correlation between the return of rhodopsin and the return of sensitivity since in man both take 30-40 min to reach completion. In the rabbit, on the other hand, regeneration takes some 80 min (fig. 5) and it is much the same in the cat (RUSHTON & BRINDLEY, oral communication 1952). This again fits the return of sensitivity, for BARLOW, FITZHUGH & KUFFLER [3] have found 90 min to be period over which the cat's threshold in the dark continues to fall.

But though there seems to be some connexion between the recovery of sensitivity and the regeneration of rhodopsin it is certainly *not* due simply or significantly to the diminished quantum-catching power of partly bleached rhodopsin. At 7 min after intense bleaching half the rhodopsin has regenerated, thus the threshold should have fallen to twice the final dark adapted level if quantum absorption alone is concerned. But in fact at 7 min after intense light adaptation the rods, if functional at all, have a threshold many hundreds of times greater than the final value.

Clearly, between the catching of light quanta by

rhodopsin and the resulting modification of impulse rhythm in optic nerve fibres there is a complicated and highly non-linear mechanism whose properties alter profoundly during light and dark adaptation. It might be possible to show that these properties are uniquely determined by the instantaneous rhodopsin level, and in what way. If this were done there would be justification for using the scotopic threshold to measure rhodopsin concentration.

The expenses of these researches were assisted by grants from the Royal Society, the Medical Research Council and the Ross Foundation to whom it is a pleasure to express our gratitude.

We should also like to acknowledge our indebtedness to Mr CLIVE HOOD who has helped in the work and constructed much of the equipment.

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Lettres à l'Éditeur

Physiologie de la télévision en couleurs *

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Le développement de la télévision pose de nombreux problèmes techniques, mais n'a pas jusqu'ici soulevé de questions nouvelles en optique physiologique. Les deux différences essentielles avec la projection cinématographique sont le découpage en lignes et la brève durée d'émission de chaque point (impulsion très courte suivie d'une trainée de phosphorescence) ; cela impose d'une part une distance minimum d'observation telle que la trame reste invisible, condition plus sévère qu'au cinéma où le diamètre de la tache élémentaire peut atteindre le double de la limite de résolution sans perte de netteté apparente ; quant à l'émission brève, elle se trouve intégrée par la rétine dont les temps élémentaires sont beaucoup plus longs.

Il semble donc au premier abord que la télévision en couleurs ne pose pas d'autres problèmes que ceux que le cinéma en couleurs a déjà résolus, mais c'est inexact pour deux raisons : d'abord la télévision peut

utiliser des procédés additifs tandis que le cinéma doit, pour des raisons pratiques, se contenter de procédés soustractifs ; ensuite l'information que peut transmettre un message télévisé est limitée par la largeur de bande autorisée et tout gain sur l'information colorée se paie par une perte d'information en détails ; il y a donc là un compromis à établir, sur lequel de nombreux techniciens ont déjà travaillé ; nous voudrions ici établir brièvement les bases théoriques de la question.

Désignons par l'unité la luminance maximum de l'écran pour le blanc, que nous supposons voisin de l'étalon C de la colorimétrie (6 740°K), parce que ce blanc constitue une « lumière du jour » raisonnable et que l'idéal de la télévision serait de transmettre sans altération les scènes d'extérieur. Admettons d'autre part les primaires instrumentales suivantes, très proches de celles que WINTRINGHAM [1] a réalisées

(*) Extrait de la communication présentée au Congrès international sur les problèmes d'optique moderne (Florence, 10-16 septembre 1954).

| | R | G | B |
|--------------------|-------|-------|-------|
| Coordonnée x | 0,680 | 0,230 | 0,145 |
| — y | 0,320 | 0,670 | 0,050 |

Un calcul ennuyeux et facile aboutit aux valeurs suivantes des luminances des primaires nécessaires pour réaliser une lumière donnée

$$\begin{aligned} Y_r &= 0,5538 X - 0,1769 Y - 0,0888 Z \\ Y_g &= -0,5590 X + 1,1879 Y + 0,0269 Z \\ Y_b &= 0,0052 X - 0,0110 Y + 0,0619 Z \end{aligned}$$

Par exemple pour réaliser le blanc C de luminance unité, soit

$$\begin{aligned} x &= 0,3101, \quad y = 0,3163; \\ X &= 0,980, \quad Y = 1, \quad Z = 1,181, \end{aligned}$$

il faut des luminances de primaires

$$Y_r = 0,261, \quad Y_g = 0,672, \quad Y_b = 0,067.$$

Ce sont d'ailleurs les luminances maxima à réaliser pour les primaires, puisque toute surface colorée dérive du blanc par suppression de certaines radiations. On constate qu'il existe un rapport 10 entre les luminances maxima du vert et du bleu.

Un vieux préjugé en optique physiologique attribue au bleu une moins bonne acuité qu'aux autres couleurs, mais cela provient sans doute des faibles niveaux généralement utilisés dans le bleu, ainsi que de l'aberration chromatique de l'œil. Après correction de la myopie au bleu et si les niveaux sont maintenus égaux, les mesures conduisent à peu près aux mêmes acuités pour toutes les couleurs. Or, dans le spectacle télévisé, on regarde en général l'écran à distance assez faible, ce qui permet de négliger la myopie dans le bleu. D'autre part les mesures d'acuité en fonction du logarithme de la luminance conduisent à une courbe classique présentent une portion rectiligne centrale dont la pente est voisine de 0,5 (KÖNIG, LYTHERG, etc.) ; par conséquent si on admet que l'acuité 1 est obtenue pour une image en vert sur noir de luminance maximum, l'image en bleu sur noir de luminance 10 fois moindre pourra se contenter de l'acuité 0,5 ; ce rapport 2 des acuités me semble d'ailleurs un maximum, car l'augmentation de la luminance de l'écran conduira dans l'avenir à utiliser sans doute des portions moins inclinées de la courbe d'acuité.

Le cas d'images monochromes sur fond noir est évidemment exceptionnel ; un autre cas limite, peut-être plus proche de la réalité, serait celui d'une image de luminance constante où seule la chromaticité varierait ; on possède peu de données sur l'acuité purement chromatique ; une étude de MACADAM aux anneaux de LANDOLT [2] donnait des acuités moins bonnes qu'en blanc et noir ; BEDFORD [3] trouve que, pour

une acuité unité en blanc et noir, les acuités chromatiques seraient comprises entre 0,2 et 0,4, mais j'ai montré que ces résultats étaient critiquables [4]. Les résultats de BOUTRY et BILLARD [5] conduisent au contraire à des acuités du même ordre par variation de luminance ou variation de chromaticité, du moins aux forts niveaux.

Du point de vue théorique, il faut d'ailleurs remarquer que, dans le bleu, l'aberration chromatique de l'œil risque de transformer des variations de couleur en variations de luminance, par décalage du test ; pour éviter cet inconvénient, O'BRIEN et MILLER [6] ont imaginé de prendre comme test deux systèmes de franges d'interférences intercalés sur la rétine elle-même ; une technique moins compliquée serait l'emploi de la lumière dirigée, et des essais ont lieu actuellement par cette méthode (DURUP). En attendant des résultats encore incertains, le mieux serait probablement de supposer que l'acuité varie comme le nombre d'échelons différentiels chromatiques qui séparent les détails contigus ; en gros, j'ai montré [4] qu'il y avait deux fois moins d'échelons entre deux primaires qu'entre le blanc et le noir, au maximum de luminance. Il semble donc raisonnable, ici encore, d'admettre un rapport 2 des acuités nécessaires à la vision des détails achromatiques et à celle des détails purement chromatiques.

La conclusion de cette brève étude — qui, je le répète, est théorique et ne s'applique qu'aux conditions optima, toute considération technique étant volontairement négligée — est que l'image colorée demande certes une moindre finesse qu'en blanc et noir, mais que la variation est au maximum dans le rapport 2 ; bien qu'appréciable, ce facteur 2 ne correspond peut-être pas à l'espoir des techniciens de barier avec des teintes presque plates un dessin en blanc et noir ; l'œil est si content de voir de la couleur qu'une telle image serait sans doute acceptée, au début, avec plaisir, mais il ne faut pas invoquer l'optique physiologique pour tenter de justifier des compromis de commodité.

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Au sujet de l'augmentation de la valeur de la myopie nocturne aux niveaux inférieurs à 10^{-3} cd/m² (*)

ALEXANDRE IVANOFF et M^{lle} CLOTILDE BOURDY

Nous avons laissé entendre dans un article précédent que le mécanisme de la myopie nocturne aux niveaux inférieurs à 10^{-3} cd/m² était peut-être lié à l'existence de la convergence binoculaire nocturne [1]. L'accommodation du cristallin observée dans l'obscurité totale par J. M. OTERO [2] se produirait en fait d'une façon progressive aux niveaux inférieurs à 10^{-3} cd/m², et serait liée à la convergence binoculaire nocturne.

| Observateur | Valeur de la convergence limite dans l'obscurité (en dioptries) | Valeur de la myopie nocturne (en dioptries) | | |
|-------------|---|---|---------------------------------------|--|
| | | à 10^{-3} cd/m ² | à $5 \cdot 10^{-5}$ cd/m ² | variation entre 10^{-3} et $5 \cdot 10^{-5}$ cd/m ² |
| J. C. | 0,05 | 0,25 | 0,50 | 0,25 |
| A. I. | 0,75 | 0,85 | 1,0 | 0,15 |
| C. B. | 1,65 | 0,55 | 1,45 | 0,90 |
| R. C. | 1,85 | 0,35 | 1,05 | 0,70 |
| L. V. | 1,95 | 0,60 | 1,20 | 0,60 |
| M. A. | 2,05 | 0,45 | 1,20 à 10^{-4} cd/m ² | 0,75 entre 10^{-3} et 10^{-4} cd/m ² |
| G. O. | 3,95 | 0,25 | 1,60 | 1,35 |

(*) Extrait de la communication présentée au Congrès international sur les problèmes d'optique moderne (Florence, 10-16 septembre 1954).

Pour essayer de vérifier cette hypothèse, nous avons étudié la myopie nocturne de 7 sujets dont nous avons précédemment mesuré la convergence binoculaire. Le tableau ci-contre traduit les résultats que nous avons obtenus.

On voit qu'à 10^{-3} cd/m² la valeur de la myopie nocturne n'excède en aucun cas 0,85 δ , et par conséquent peut être expliquée uniquement par les aberrations chromatique et sphérique de l'œil, jointes respectivement à l'effet PURKINJE et à la dilatation de la pupille. Entre 10^{-3} cd/m² et $5 \cdot 10^{-5}$ cd/m², la valeur de la myopie nocturne n'augmente que de 0,25 δ ou moins pour les deux sujets dont la convergence binoculaire nocturne est faible, elle augmente de plus de 0,5 δ pour les quatre sujets dont la convergence binoculaire nocturne est de l'ordre de 2 δ , et enfin elle augmente de plus de 1 δ pour le sujet G. O., dont la convergence binoculaire nocturne est particulièrement forte. Ces résultats se trouvent donc en accord avec l'hypothèse d'une accommodation progressive du cristallin aux niveaux inférieurs en gros à 10^{-3} cd/m², accommodation qui serait étroitement liée à la convergence binoculaire se produisant aux mêmes niveaux.

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Mesures photométriques visuelles sur un champ à gradient d'éclairement variable (*)

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On a étudié un champ dont la luminance varie dans une direction : elle a une valeur constante L_1 jusqu'au point S_1 , descend linéairement jusqu'au point S_0 de luminance L_0 presque nulle, puis reste constante.

Avant toute mesure, on voit immédiatement une distribution d'éclairement complètement différente de celle que l'on attendait : deux lignes fines apparaissent, l'une brillante, à la limite entre la pénombre et le champ clair, l'autre noire, au bord de l'ombre. En outre, une grande partie de la pénombre semble très lumineuse, plus même que le champ éclairé.

(*) Cette recherche a été effectuée avec la subvention de l'European Office of the Air Research and Development Command (U. S. A. Air Force) selon le contrat A. F. 61 (514)-634 C. passé avec l'Istituto Nazionale di Ottica.

Ce phénomène fut découvert par MACH [1], et étudié ensuite par de nombreux chercheurs [2, 3, 4, 5, 6, 7, 8, 9, 10], mais personne n'avait fait une étude quantitative de la luminance visuelle.

Le dispositif utilisé est très simple. Une surface blanche diffusante est éclairée par une source rectangulaire uniforme. Un écran opaque E dont un bord rectiligne est parallèle à un des côtés de la source, projette une ombre sur le diffuseur et produit la distribution d'éclairement cherchée.

Pour mesurer la luminance en une région du champ, on projette sur celui-ci plusieurs points lumineux alignés parallèlement à la direction le long de laquelle la luminance est constante (on a préféré adopter cette

méthode plutôt que de projeter un seul point, car dans ce cas, la fixation est plus difficile et moins assurée). Ces points lumineux peuvent se déplacer dans le champ de quantités mesurables, dans la direction de variation de la luminance, et leur luminance varie au moyen d'un coin photométrique. L'observateur rend les points plus brillants que le champ, puis fait diminuer leur luminance, et note le moment exact où ils disparaissent. Les mesures ont été faites en vision binoculaire, par deux observateurs (A. F., M. J.). Les résultats sont représentés par les courbes de la figure 1. On a porté en abscisses la distance angulaire sur le diffuseur en millièmes de radian et, en ordonnées, la luminance des points à l'extinction (en échelle arbitraire). On a dessiné en pointillé la forme objective de la courbe en prenant d'une manière un peu arbitraire, comme niveau supérieur L_1 , la luminance que l'on mesure sur le diffuseur avec le même procédé d'extinction, quand l'écran E est enlevé, et comme niveau inférieur L_0 , la luminance mesurée dans la partie noire du champ loin de la pénombre. Les points S_0 et S_1 ont été déterminés expérimentalement.

Les courbes obtenues montrent qu'avec cette méthode on arrive à donner une description quantita-

tive de la distribution subjective de luminance vue par l'observateur, dans la pénombre et dans la partie claire du champ, mais non dans la partie noire.

C'est une opinion très répandue que la réponse donnée par l'œil, avec une bonne approximation, est une fonction croissante de l'éclairement. Les résultats que l'on vient de rapporter montrent que cette loi n'a pas une valeur générale ; ce ne peut être non plus une loi approchée, car les écarts mesurés sont très sensibles. Il semble que d'autres facteurs interviennent, aussi importants que l'éclairement, notamment le *gradient* d'éclairement et ses variations. A ce propos, il faut remarquer que, jusqu'ici, les auteurs qui ont étudié le phénomène ont insisté surtout sur la présence de la ligne brillante, tandis que, selon notre opinion, il est beaucoup plus important que presque toute la pénombre ait une luminance subjective plus grande que le champ complètement éclairé. On pourrait peut-être supposer que le gradient d'éclairement produit toujours l'effet d'augmenter la luminance, et ce fait pourrait avoir une grande importance dans la vision à travers les instruments d'optique chaque fois qu'il y a de l'œil-de-chat.

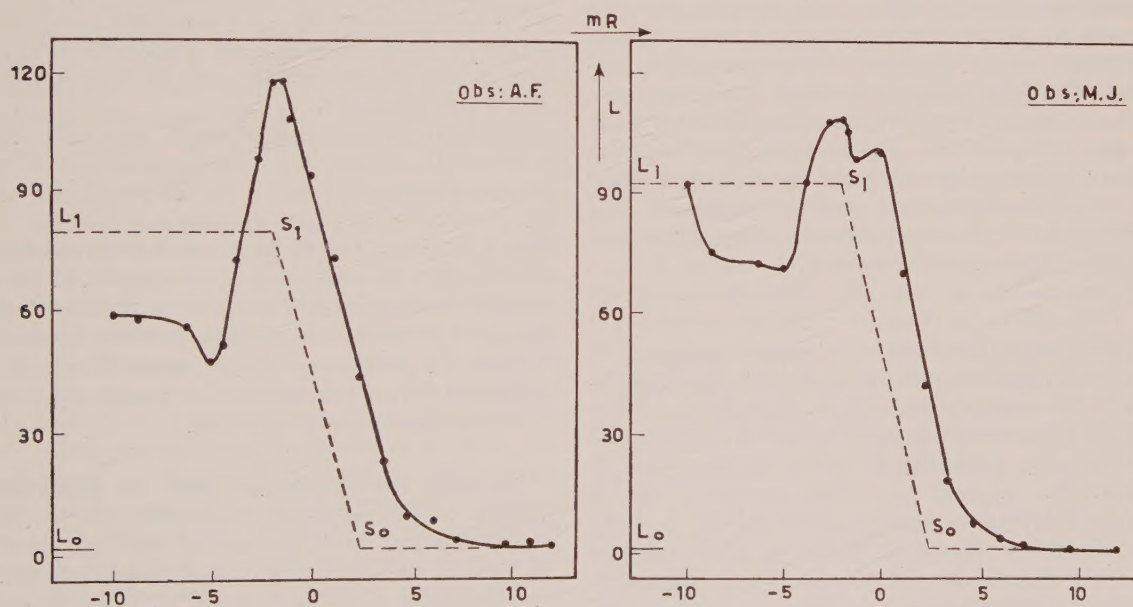


FIG. 1.

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Congrès International sur les problèmes d'optique moderne. Florence, 10-16 septembre 1954.

(Florence Meeting on Problems in Contemporary Optics)

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Un Congrès International sur les Problèmes actuels en Optique a eu lieu à Florence du 10 au 16 septembre ; il était organisé par l'« *Istituto Nazionale di Ottica* » d'Arcetri.

Des travaux des pays suivants ont été présentés : Allemagne, Autriche, Belgique, Danemark, Espagne, Etats-Unis d'Amérique, France, Grande-Bretagne, Inde, Italie, Japon, Hollande, Suisse, Tchécoslovaquie, Yougoslavie. Une soixantaine de communications et 4 rapports d'ensemble ont été présentés.

Comme l'indique le titre du Congrès, celui-ci a été entièrement consacré à l'étude des problèmes nouveaux et d'actualité. Pour la première fois, lors d'une réunion internationale d'Optique, presque tous les problèmes classiques et longtemps débattus ont été délibérément écartés. On a préféré, plutôt que de suivre une voie bien connue, préciser quelques voies nouvelles, ouvertes ces dernières années ; il a donc été traité de questions du domaine de l'Optique pure, mais encore plus de questions soulevées après un heureux rapprochement entre l'Optique et une science ou une technique modernes, rapprochement dans lequel l'apport est réciproque.

La séance inaugurale a eu lieu à la Salle S. Apollonia de l'Université de Florence ; elle fut ouverte par le Commissaire du Gouvernement auprès de l'Institut d'Optique, G. ABETTI qui définit le but du Congrès. La parole fut donnée ensuite à M. VAN HEEL, Président de la Commission Internationale d'Optique et à M. G. POLVANI, Président de la Société Italienne de Physique. M. V. RONCHI, Directeur de l'Institut d'Optique d'Arcetri fit ensuite un exposé sur « *l'Optique de Francesco Maria Grimaldi* », dans laquelle après avoir rappelé la découverte de la diffraction par GRIMALDI, l'auteur exposa les conséquences qui en découlèrent aux siècles suivants, jusqu'au triomphe de la théorie ondulatoire. Les autres séances du Congrès se sont tenues à l'Institut d'Optique.

Les thèmes mis à l'étude étaient les suivants :

Optique et théorie de l'Information. — La théorie de la mesure et de la transmission de l'information, née et développée particulièrement dans le domaine des communications électriques, commence à s'introduire en Optique. Les premières tentatives de leur utilisation faites à des points de vues variés, dans des pays différents, tentatives qu'il est intéressant de confronter, furent présentées.

L'Ecole algéroise de A. BLANC-LAPIERRE et M. PERROT a utilisé les méthodes de l'analyse harmonique et de la radiotechnique pour suggérer un moyen d'améliorer le pouvoir séparateur d'un instrument.

E. H. LINFOOT a étudié la méthode à suivre pour appliquer la théorie de l'information au projet d'un instrument d'optique.

L'Ecole d'Arcetri, avec G. TORALDO et M. T. ZOLI a présenté des considérations théoriques sur la capacité d'un canal optique en présence de bruits de fond et les résultats expérimentaux sur la statistique d'une image considérée comme une source stochastique.

L'Institut d'Optique de Paris, avec A. MARÉCHAL et P. CROCE, a présenté d'intéressants résultats théoriques et expérimentaux sur l'amélioration des détails d'une image obtenue par filtrage optique des fréquences spatiales.

L'Ecole de Besançon a présenté, avec M^{lle} J. GAULTIER DU MARACHE, des considérations sur la photographie considérée comme filtre de fréquence, et, avec M. DUFFIEUX, des considérations générales sur l'extension de l'espace de fréquence et sur les problèmes qu'il faut poser à la théorie de l'information. P. FELLGETT exposa une utile application de la théorie de l'information à la mesure de la vitesse radiale des étoiles.

Enfin E. INGELSTAM fit un exposé d'ensemble très documenté sur les différentes sortes d'information qu'il faut considérer en optique.

Systèmes non classiques pour la formation des images. — Les systèmes classiques sont les lentilles et les miroirs. Tout récemment ont été découverts ou tout au moins utilisés bien d'autres systèmes. A. C. S. VAN HEEL d'une part et H. H. HOPKINS et N. S. KAPANY d'autre part ont montré des systèmes de formations d'images utilisant des faisceaux de fibres minces transparentes. Une méthode analogue est employée par M. FRANÇON pour la photométrie microscopique. G. TORALDO et LAURA RONCHI ont montré un grand nombre de systèmes optiques de microonde, résultats de la collaboration entre l'Institut d'Optique d'Arcetri et le Centre de Microondes du Conseil de Recherche Italien. En particulier, les nouveaux doublets de « conflexion » ont été présentés ; les participants au Congrès ont pu voir en visitant le Centre de Microondes, une grande partie de ces systèmes en fonctionnement.

Enfin R. C. SPENCER fit un exposé sur les récents progrès obtenus dans l'optique des microondes à l'Air Force Cambridge Research Center.

Trois dimensions et systèmes anamorphoseurs. — Ce sujet, venu à l'ordre du jour tout récemment, pour des raisons pratiques, a soulevé un grand nombre de problèmes théoriques, dans le domaine de l'optique physiologique et psychologique comme dans celui de l'optique géométrique. W. D. WRIGHT a examiné l'importance des divers facteurs tels que la différence des images rétinienne, la convergence, la parallaxe cinématique, etc. dans la perception de la profondeur. A. ARNULF étudia l'application à la projection cinématographique d'un système de photographie en relief. G. FRANKE traita de l'emploi et de la correction des systèmes de prismes anamorphoseurs. A. BOUWERS et B. S. BLAISE présentèrent un système anamorphoseur composé de miroirs.

Surfaces asphériques. — L'emploi des surfaces asphériques dans les instruments d'optique est devenu de plus en plus courant, grâce surtout aux nouvelles méthodes de fabrication. K. W. BRITTAN et J. DEMARCO présentèrent chacun une machine pour la fabrication en série des surfaces asphériques. R. E. HOPKINS fit un exposé d'ensemble sur les modes de production et sur les conditions théoriques d'emploi des surfaces asphériques dans les instruments d'optique. B. JUREK développa d'autres considérations théoriques.

Problèmes optiques de la télévision. — Il est inutile de souligner l'importance prise par ces problèmes à l'heure actuelle. La collaboration entre les chercheurs de la télévision et les opticiens est de plus en plus nécessaire. H. H. HOPKINS traite la question des objectifs à focales variables dont on connaît le rôle important dans la prise de vue en télévision. E. H. TRAUB analysa les différentes méthodes permettant la transmission de films en télévision. F. I. HAVLICEK exposa une méthode de calculs d'objectifs à grande ouverture. G. TORALDO traita d'une méthode de projection en couleurs. Y. LE GRAND analysa les questions relatives au pouvoir séparateur chromatique requis par la télévision en couleurs. G. A. BOUTRY étudia le comportement de l'œil humain devant la télévision et H. RINIA fit une relation d'ensemble sur les problèmes optiques posés par la télévision.

Problèmes rétinien. — Ce sont en réalité des problèmes classiques, mais ils ont pris ces dernières années une telle importance et ont été considérés de points de vue si nouveaux que l'on peut les traiter comme des problèmes d'actualité.

M. A. BOUMAN exposa les résultats de quelques expériences sur l'interaction dans la vision binoculaire. C. BERGER traita d'un essai de l'interaction

dans la fovéa, obtenu par papillotement. A. KÜHL étudia l'association des éléments rétinien en fonction du pouvoir séparateur. H. SCHÖBER analysa quelques résultats obtenus en employant les anneaux de LANDOLT.

R. GRANIT fit un exposé de grand intérêt sur les effets centrifuges dans la rétine. A. MANFREDI démontra la génération de phosphènes rotatoires dus à l'action de courants alternés et exposa une méthode de sensitométrie visuelle basée sur l'effet psychovoltaïque. Une contribution de grande importance fut apportée par W. H. RUSHTON avec la mesure de la variation de densité de la rhodopsine dans les différentes parties de la rétine sous l'influence de la lumière. W. D. WRIGHT traita de l'influence de la lumière diffuse dans les phénomènes d'éblouissement. F. FLAMANT exposa une méthode objective pour l'examen des images rétinien. LUCIA RONCHI montra l'influence des mydriatiques dans l'effet STILES-CRAWFORD. S. S. BALLARD parla des recherches effectuées dans son Laboratoire sur la reconnaissance des objets éloignés. M. AGUILAR et J. OLIVA traitèrent de la distribution des unités sensorielles dans la rétine extrafovéale. J. M. OTERO et J. CASAS traitèrent de la théorie des instruments de nuit. A. BIOT et A. FIORENTINI exposèrent dans deux communications différentes les phénomènes relatifs aux gradients d'illumination sur la rétine. R. W. DITCHBURN exposa une expérience sur l'influence des mouvements oculaires dans la vision. Le même sujet fut traité par A. FIORENTINI et A. M. ERCOLIS mais avec une méthode différente. E. INGELSTAM fit un exposé sur la structure microscopique des récepteurs rétinien et sur l'éventuelle interprétation électrique. A. IVANOFF présenta une étude sur les actions réflexes de la rétine sur la dioptrique oculaire.

Questions diverses. — Bien que le Congrès ait été explicitement consacré aux sujets indiqués ci-dessus, les communications sur divers sujets de l'Optique, présentant un intérêt particulier, n'en ont cependant pas été exclues. J. W. PERRY parla de monochromateurs ; D. RICHARDSON, de réseaux de diffraction ; A. C. S. VAN HEEL, de la récente éclipse solaire et de doublets à un rayon de courbure ; F. GABLER, sur le contraste de phase ; J. PICT de la réflexion totale ; W. FRANZ, de la diffraction ; C. MORAIS, de l'application du calcul homographique au calcul optique ; A. ARNULF, O. DUPUY et F. FLAMANT, du système optique de l'œil ; M. FRANÇON, de l'examen interférométrique des états de surface ; H. H. HOPKINS, des images de diffraction et des images des objets incohérents ; M. M. CORRIAS, du calcul des doublets.

C'est le Professeur J. M. OTERO qui présenta, en conclusion, les observations et les résultats que l'on pouvait attendre du Congrès.

A l'occasion du Congrès avaient été organisées différentes manifestations : visite de la ville, de la Galerie des Offices avec éclairage de nuit, dîners officiels,

cocktail et en dernier lieu une journée à Lucca, Forte dei Marmi et Pise.

En tant que participant au Colloque, je suis heureux d'ajouter quelques mots au sommaire précédent, qui ne mentionne que les faits saillants et ne peut évoquer l'atmosphère d'amitié cordiale que tous les assistants ont goûtée. Ceux-ci ont emporté les souvenirs les plus agréables de ce contact avec de nombreux amis opti-

ciens venus de presque toutes les parties du monde, contact renoué dans une ambiance dont la tradition profonde de culture nous a remplis de joie et d'admiration. Les organisateurs florentins du Colloque ont toute raison de se féliciter du succès de cette réunion à laquelle ils ont apporté tant de soin qu'elle restera mémorable pour tous ceux qui y ont participé.

A. C. S. VAN HEEL.